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The role of geology in the transition to clean energy – The contribution of hydrogen and carbon capture, storage and utilisation

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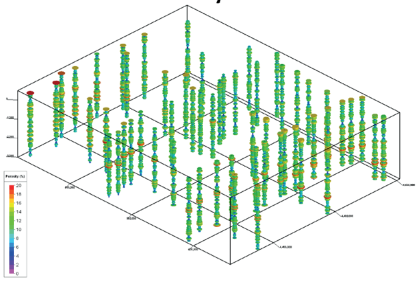
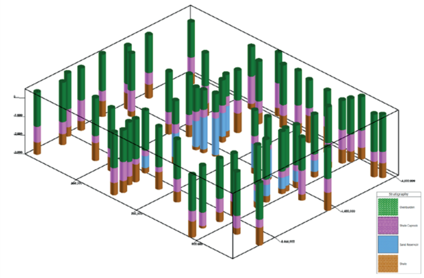
Using RockWorks to Determine the Capacity of a Carbon Storage Reservoir

RockWorks Borehole Database

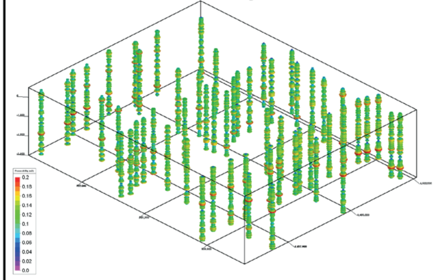
Porosity Data



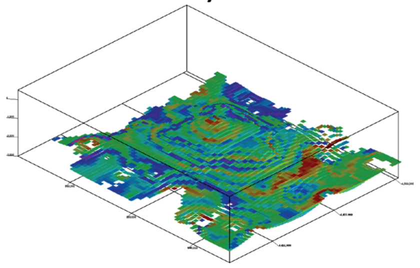
Stratigraphy Data



Permeability Data

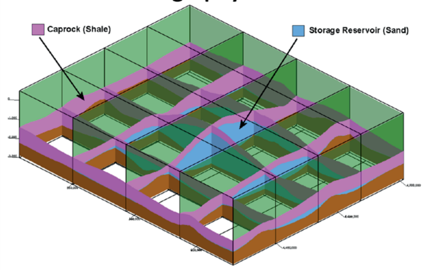


Porosity Model



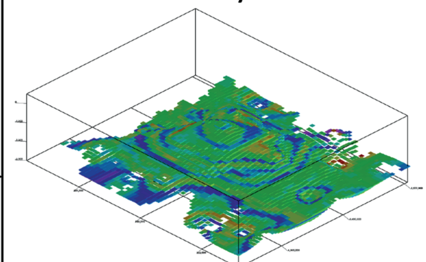
A porosity block model was interpolated from downhole data and constrained by the sand unit extents.

Stratigraphy Model



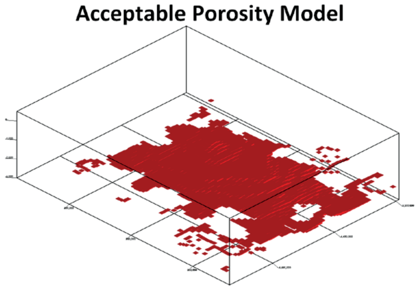
A stratigraphic model defining the caprock (shale) and host-rock (sand) was interpolated from downhole data.

Permeability Model



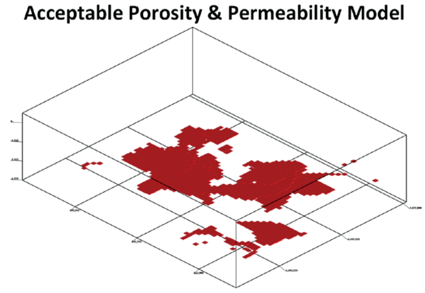
A permeability block model was interpolated from downhole data and constrained by the sand unit extents.

Acceptable Porosity Model



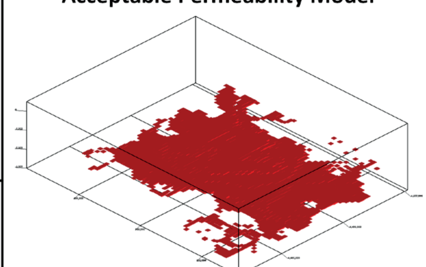
The porosity model was converted to a Boolean (true/false) model based on a cutoff value of 10%.

Acceptable Porosity & Permeability Model



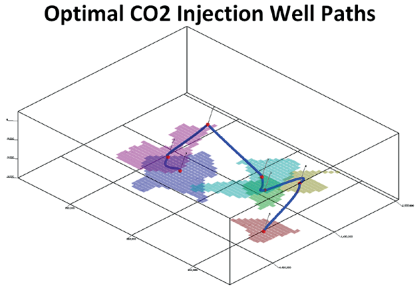
Multiplying the two Boolean models creates a spatial model depicting where both parameters are acceptable.

Acceptable Permeability Model



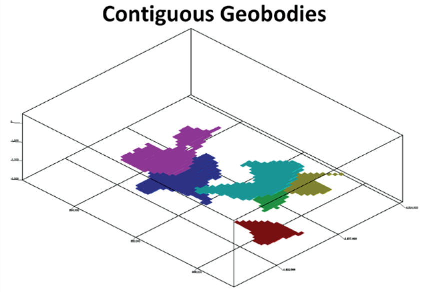
The permeability model was converted to a Boolean (true/false) model based on a cutoff value of 0.1 millidarcies.

Optimal CO2 Injection Well Paths



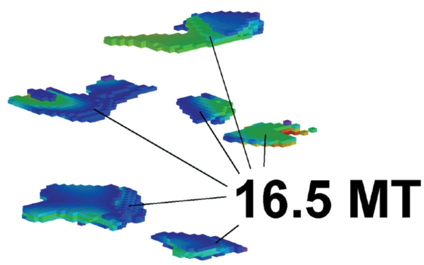
The optimal path algorithm was used to plan deviated injection wells to deliver CO2 to the six largest geobodies.

Contiguous Geobodies



The Geobody filter was used to identify the six largest connected zones of acceptable porosity and permeability.

Storage Capacity Computation



The composite Boolean model was multiplied by the porosity model to compute the storage capacity.

Contents

Peer review:
We would like to express a particular thanks to all those who participated in the peer reviewing of this issue and thus contribute to the improvement of the standards of the European Geologist journal. The articles of this issue have been reviewed by Eva Hartai, Gareth Jones, Nikoloas Koukouzas, Mate Osvald, Monica Sousa and Angelo Statti.

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Foreword

EurGeol. Marko Komac, EFG President

Dear Reader,

It is my great pleasure to welcome you to the latest and trendiest professional geologist's journal! Just like the previous edition, this edition of the *European Geologist* journal continues with geology-related topics that support (or could support) the challenges Europe faces due to its commitment to the green transition. In the 55th EGJ edition we delve into two strongly related topics – carbon capture, utilisation, and storage (CCUS), and hydrogen utilisation and storage (HCUS).

Both concepts are underexplored and understudied, yet the up-to-date research, analyses and test studies indicate promising development of methodologies and their utilisation at large-scale levels. The four articles in this issue cover the whole spectrum of CCUS and HCUS capabilities, ranging from the conceptual level, to the significance of the methods in the energy transition and real-case assessment and early-stage feasibility studies. The common conclusion of all articles is that the two methodologies could, if implemented correctly and under careful consideration of geological boundary conditions, notably contribute to the objectives of the European Green Deal.

Without any doubt, to reach the objectives of the Green Deal, the European Union must incorporate a plethora of approaches. Here, we present only a handful of potential solutions through which geologists contribute to tackling the immense challenges of the energy transition. Yet, at the end of the day, it is upon the geological community to present the aforementioned solutions properly, transparently, and effectively to stakeholders and decision-makers. Only if this is done in an accurate and compelling way, will the outcome be positive and the impact notable.

In my final preface of the EGJ, I would like to extend my heartfelt wishes to all my geological and geoscience colleagues in their endeavours, careers, and private lives and that their actions may have a positive impact on their families, friends, communities, and the society. I also invite you to enjoy reading the latest edition of the European Geologist, get inspired by its content and effectively use your potential to make notable and beneficial changes in the world.

Thank you for enabling me to serve the EFG family for the past six years.

Marko Komac, EurGeol 1294

Past-President of EFG

The place of natural hydrogen in the energy transition: A position paper

Eric C. Gaucher[1,], Isabelle Moretti[2], Nicolas Pélissier[3], Glen Burridge[4] and Nicolas Gonthier[5]*

https://doi.org/10.5281/zenodo.8108239

*Natural Hydrogen is a new, clean and low-carbon source of hydrogen that is produced by the Earth, and can migrate and accumulate in geological reservoirs. Its exploration has begun in many countries and its price could be significantly lower than other H_2 sources. In this position paper, the **earth₂ initiative** summarizes (i) what natural hydrogen is, (ii) how we explore and produce it, (iii) the benefits of this new resource, (iv) the maturity of the technology, (v) the presence of a very active community, (vi) the potential growth for this business, (vii) the need for regulatory evolution and appropriate taxonomy at European level and (viii) the next steps in natural H_2 development, considering the needs for investments in demonstration systems and pilots.*

*L'hydrogène naturel est une nouvelle source d'hydrogène propre et à faible teneur en carbone qui est produite par la Terre et qui peut migrer et s'accumuler dans des réservoirs géologiques. Son exploration a commencé dans de nombreux pays et son prix pourrait être nettement inférieur à celui des autres sources de H_2. Dans cette prise de position, l'**initiative earth₂** résume (i) ce qu'est l'hydrogène naturel, (ii) comment nous l'explorons et le produisons, (iii) les bénéfices de cette nouvelle ressource, (iv) la maturité de la technologie, (v) la présence d'une communauté très active (vi) le potentiel de croissance de cette activité, (vii) la nécessité d'une évolution réglementaire et d'une taxonomie appropriée au niveau européen et (viii) les prochaines étapes du développement naturel de H_2, compte tenu des besoins d'investissements dans des systèmes de démonstration et de projets pilotes.*

*El Hidrogeno Natural es una fuente nueva, limpia y de bajo carbono, que es producida por la Tierra, que puede migrar y acumularse en reservorios geológicos. Su exploración ha comenzado en muchos países y su precio puede ser significativamente más bajo que otras fuentes de H_2. En este trabajo, la **iniciativa earth₂** resume (i) que es el hidrogeno natural, (ii) como se explora y produce, (iii) los beneficios de este recurso, (iv) la madurez de esta tecnología, (v) la presencia de una comunidad muy activa, (vi) el potencial crecimiento de este negocio, (vii) la necesidad de una evolución regulatoria y la taxonomía adecuada a nivel europeo y, (viii) los siguientes pasos en el desarrollo natural del H_2, considerando las necesidades de inversión en sistemas pilotos y de demostración.*

1. What is Natural Hydrogen? Where can we find it?

The Earth continuously produces natural H_2 (also called Native H_2) through several chemical reactions that are primarily related to the oxidation of ferrous iron minerals, radiolysis of water, maturation of organic matter and the outgassing from the Earth's mantle:

- Redox reactions related to the presence of ferrous iron in certain minerals or to ferrous iron dissolved in aquifers are the most efficient processes for producing H_2. In these reactions, the ferrous iron rusts and scavenges oxygen from the water, releasing hydrogen (eq. 1):

$$2\,FeO + H_2O = Fe_2O_3 + H_{2(aq)} \quad \text{(eq.1)}$$

These reactions can be made with (a) dissolved ferrous iron, (b) olivine and pyroxene minerals of the Earth's Mantle (serpentinisation), (c) ferrous iron-rich minerals of the Earth's crust (Biotite, Amphiboles, Pyrite, Pyrrhotite, Magnetite, etc…), and to a lesser extent, with ferrous iron-rich carbonates (Siderite, Ankerite) [1].

- The radiolysis of water produces H_2 by splitting the water molecule through radiation emitted by the decay of natural radioactive atoms (U, Th, etc…) present in several types of rocks [2, 3].
- The Earth stored hydrogen during its primordial accretion, in the form of hydrides that could gradually decompose and support continuous H_2 outgassing over geologic time [4].
- Over-maturation of organic matter can generate natural H_2 [5].
- The decomposition of volcanic H_2S gas into H_2 and SO_2 explains the concentrations obtained in the fumaroles of volcanos [1].

The exploration strategy for hydrogen should focus on areas where ferrous iron and/or natural radioactivity is present and can react with water [6, 7]. Magmatic rocks are therefore of primary importance, and many occurrences of H_2 seepages are known on continental or offshore regions related to these rocks. In an exhaustive

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TRL Native H_2 Exploration/Production

0 Discovery of H_2 at the Earth surface	Done
1 Systematic research of H_2 seepages in various environments	Done
2 Short time monitoring of sites	Done for 2-3 sites
3 Understanding of the origin of H_2	Done for 2-3 sites
4 Small Scale prototype of permanent H_2 fluxes / Numerical modelling of the H_2 permanent seepages Global understanding of the Hydrogen system	In Progress in Academia
5 Median Scale prototype (1200 m) Perennial production of a demonstrator over several years	Hydroma (Mali)
6 First deep borehole (3000 – 5000 m)	Natural hydrogen energy LLC Desert Mountain Energy
7 First Exploration plan at regional scale First delineation / Several boreholes	In progress Santos (Australia)
8 Prototype of Production of the first discovery	No
9 Scaling-up / Commercial exploitation	No

Figure 1: Evaluation of the technology maturity using the Technology Readiness Levels (TRL) method.

review, Zgonnik (2020) [8] recorded H_2 occurrences in 465 geo-references worldwide. Extensive reviews of available data are also being conducted on a national level, for example in Australia [9].

Two emblematic sites can illustrate the potential of natural H_2:

- The Bourakebougou site (Mali) has 12 positive boreholes with pure H_2 (98%) over a surface of 50 km² [10].
- In Iceland, geothermal power plants emit a total of 1.2 kt H_2 per year into the atmosphere. If we consider a price of H_2 for 2€/kg, the natural H_2 emitted by the existing power plants corresponds to a value of €2.3 M/yr [11].

Natural H_2 is a viable resource that is observed as being relatively well distributed across the Earth's surface. Economic reserve assessments are underway in some locations.

N.B.: In this paper, we use the expression "Natural hydrogen" but this is equivalent to Native Hydrogen, GeoH_2 or White Hydrogen. We also find "Gold Hydrogen" in some publications for the same natural origin.

2. How do we Explore and Produce Natural H₂?

The geological exploration of H_2 follows the same approach as for hydrocarbons, starting with the identification of the source rock, followed by the migration pathways, and finally the reservoirs and traps. For the latter, formations such as volcanic sills, clays or salt layers could potentially be capable of trapping hydrogen in crystalline or sedimentary rocks, for example, at the bottom of the sedimentary basins.

In the case of Bourakébougou, boreholes of less than 1000 m seem to be effective in finding significant quantities of natural hydrogen. However, H_2 is a very reactive molecule, that can be consumed by many oxidants, and therefore, it is destroyed during its migration. Bacterial growth can also be promoted by natural hydrogen, as it acts as an energy provider for the microbes. Therefore, a temperature above 120°C can preserve the resource by eliminating microbial activity while increasing the kinetics of the reactions. Future exploration and production schemes should integrate the chemical and biological reactivity of this molecule. However, if the H_2 flux is high, the reactivity of the molecules will be less crucial.

Some players are also contemplating the co-production of He with natural H_2, as they are commonly found together. Geothermal power plants could enhance their value chains by co-producing natural H_2 and mineral substances, such as lithium. Coupling H_2 production with the storage of CO_2 in ultrabasic rocks will add additional benefits to natural H_2 production [12].

3. The benefits of Natural Hydrogen

The earth$_2$ members are convinced that the energy transition requires all sources of clean hydrogen to succeed. Natural hydrogen offers specific advantages:

1. Natural hydrogen is clean, as there is no carbon in the production chain, and does not require anthropogenic electricity or water. Furthermore, extraction and separation at production sites have a limited footprint.
2. It is not an energy vector, but a resource in itself, and does not require the destruction of one energy source for another. It does not depend on anthropogenic energy or specific raw materials.
3. Recent research targeting various countries worldwide suggests the presence of multiple viable plays and cost-effective exploitable resources.
4. The production sites available within the European continent, such as France, Spain, Italy, Poland and Romania, offer diversity and flexibility. It can complement other low carbon H_2 production means and it can contribute to securing energy supply and avoiding the supply's intermittency.
5. Natural H_2 does not require purified water (electrolysis-based Green H_2

production), or CO_2 storage (Blue H_2). Additionally, it does not involve waste disposal (nuclear-driven Pink H_2).

6. No production intermittency.
7. The production costs of natural H_2 are expected to be lower than all other forms of proposed H_2 production, which can help in unlocking the hydrogen economy [12]. The very competitive production cost is reinforced by a joint valorisation potential of resources, such as helium, geothermal energy and high-value brines.

4. Maturity of the Technology

Our ultimate goal is to produce a commercial H_2 resource at a limited cost and with minimal environmental impacts. To achieve this, we can use the Technology Readiness Levels scale (TRL) to assess its maturity (Figure 1).

We assign a TRL of 9 to the ultimate achievement of commercial production of natural H_2.

The TRL 0 corresponds to the discovery of H_2 seepages at the Earth's surface, with the idea that larger volumes can be produced underground [14].

The TRL 1 corresponds to the systematic search of H_2 seepages in various geological environments [8].

The TRL 2 corresponds to the first short-term monitoring of H_2 fluxes [7, 15].

The TRL 3 corresponds to a global understanding of the origin of H_2 emissions in continental settings, as demonstrated by the model of production proposed by Lefeuvre et al. [16] for the West Pyrenees, or the potential for economic production of natural H_2 in the geothermal fields of Iceland [11].

The TRL 4 corresponds to the implementation of permanent monitoring sites that couple hydrogeology, hydrochemistry and gas chemistry in very well-characterised geological structures coupled with well tests to determine the reserve volume.

The TRLs 5 and 6 correspond to investments that will enable to access depths where active H_2 production processes are taking place. A TRL 5 or 6 can be assigned to the Bourakébougou site in Mali [10, 17], where perennial H_2 production has been demonstrated with 12 wells showing its presence. However, the local company HYDROMA has not reported a reserve estimate at the production site.

After delineation at a regional scale (TRL7), commercial production tests can be carried out (TRL 8), and finally, the H_2 gas can be commercialised (TRL9). Several exploration companies are making rapid progress towards this ultimate goal.

5. A Very Active Scientific Community

A scientific community dedicated to natural H_2 already exists in France, the United Kingdom, the USA, Brazil, Australia and other countries. This community consists of research groups that have worked on water-rock interaction processes (such as serpentinisation and radiolysis) or economic geology (such as in oil and gas or mining industries). The number of publications presenting data showing explicit natural H_2 presence in soils, aquifers or wells is rapidly increasing (Figure 2).

A dedicated congress now exists on this subject (H-Nat), which was held online in 2021 and 2022. Special sessions have been organised at the AAPG Europe Regional Conference in Budapest (May 2022), at the Goldschmidt Conference in Hawaii (2022) and in Lyon (2023).

6. Potential Growth of a Natural Hydrogen Business

The economic sector is in the process of being structured for natural H_2 and the earth$_2$ initiative is a good example of this in Europe. The earth$_2$ initiative brings together energy groups like Engie, exploration and production start-ups such as 45-8 Energy, H_2Au, Helios Aragon, service providers including the CVA group and Schlumberger, and independent consultants. The earth$_2$ initiative is composed of 40 members actively working in this field. This initiative was born under the aegis of the Avenia cluster and these actors develop exploration methods, geochemical sensors and geophysical methods dedicated to natural H_2 exploration. earth$_2$ is a forum for fruitful discus-

Figure 2: (a) Progress of the number of publications related to natural H_2 and (b) repartition of natural H_2 publications by country.

sions on the commercial development of natural H_2 through permanent working groups, workshops and field trips, launching innovative, and collaborative projects and lobbying public institutions.

In Australia, several start-ups and oil and gas companies now have an exploration strategy for natural H_2, including Petrex, Buru Energy and Gold Hydrogen. In South Australia, more than 20 permits have been applied for, with two already granted to Gold H2 and one to H2EX. The first wells are expected in 2023. Further north, in the Amadeus Basin, Santos, an oil company, has "accidentally" encountered a mixture of methane, helium and hydrogen and will drill three wells in 2023 to evaluate the resource.

In the USA, two companies have reported significant discoveries: Natural Hydrogen Energy LLC in Nebraska in 2019 and Desert Mountain Energy in Arizona in 2022.

By the end of 2022, 27 companies have been identified as active in natural hydrogen exploration, up from three companies three years ago.

The American Association of Petroleum Geologists has also established a "Natural Hydrogen" task force led by the US Geological Survey. Meanwhile, the International Energy Agency has accepted a technical task on natural H_2 in its H_2 collaboration program.

The costs of natural hydrogen production are expected to be significantly lower than the production costs of steam-methane reforming (brown H_2: 1.5$/kg). Indeed, the exploration and production costs of natural hydrogen are anticipated to be very similar to those of natural gas, without the need for refinery transformation or CO_2 storage (blue hydrogen: 3$/kg = brown H_2 + costs of CO_2 storage). Currently, green H_2 from renewables costs over $6/kg and requires electricity transformation that could be used directly for other purposes. Our best estimate for the price of natural H_2 is less than $1/kg.

7. Regulatory Aspects of H_2 Exploration

The development of H_2 exploration requires changes in legislation to allow companies to obtain permits and perform exploration works. Mali is a pioneer country, where the first permit was granted in the area of Bourakébougou in 2017. South Australia opened its mining code to natural hydrogen exploration in 2021. In April 2022, it was France's turn to include natural H_2 as a natural resource in its mining code and the US law on natural substances also appears to be flexible enough to allow for H_2 exploration permits.

8. Recommended Next Steps of Natural H_2 Development

Natural Hydrogen is a topic that is rapidly shifting from pure research to economic development. This new energy source is clean with very low-carbon emissions and should be considered as a form of renewable hydrogen in European taxonomy. Its potential is already demonstrated and significant volumes have been identified in regions such as Iceland, Mali and the Pyrenees, where exploration licenses have been granted. However, public support is still needed to develop demonstration systems and pilots in promising areas. Access to financing means, available for the hydrogen economy, could accelerate the maturity and the number of projects. Ultimately, regulation changes are required to facilitate the development of this subject.

The members of the $earth_2$ initiative are optimistic about the potential for this new resource and believe that it will require support to demonstrate and contribute to the energy transition.

Author Contributions: "Conceptualisation, $earth_2$ initiative management board; methodology, all authors; validation, $earth_2$ initiative management board; writing—original draft preparation, E.C.G.; review and editing, I.M, N.P., G.B., N.G.; visualisation, E.C.G., N.P.; All authors have read and agreed to the published version of the manuscript."

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Acknowledgments: $earth_2$ initiative, Pôle Avenia.

Conflicts of Interest: The authors are all members of the $earth_2$ initiative promoting the development of natural H_2 exploration and production.

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Techno-Economic Evaluation of Carbon Capture, Utilisation and Storage; Case Study of Scenarios in Western Macedonia, Greece

Nikolaos Koukouzas [1,], Rania Karametou [1], Dimitrios Karapanos [1], George S. Maraslidis [1], Pavlos Tyrologou [1], Paula Coussy [2], Anders Nermoen [3], Julio Carneiro [4], Paulo Mesquita [4] and Paula Canteli [5]*

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Over the previous decades, the region of Western Macedonia in Greece has become home to heavy industrial clusters. Carbon capture, utilisation, and storage (CCUS) is an essential technology for climate change mitigation that could deliver significant economic growth. As part of the EU-funded STRATEGY CCUS project (2019-2022), two scenarios were developed and economically evaluated for the deployment of CCUS technologies in Western Macedonia. These scenarios were created using a novel software tool to analyse the CCUS business model in the Greek region. For this, two suitable local onshore geological sites were utilised for storing captured CO_2. Five industries from different industrial sectors have been chosen for CO_2 utilisation. Key Performance Indicators (KPIs) were calculated to measure this project's long-term value and return on investment (ROI) while also measuring its short-term efficiency and profitability over the deployment process lifetime.

Au cours des décennies précédentes, la région de Macédoine occidentale en Grèce est devenue le foyer de pôles industriels importants. Le captage, l'utilisation et le stockage du carbone (CCUS) est une technologie essentielle pour l'atténuation du changement climatique qui pourrait générer une croissance économique significative. Dans le cadre du projet STRATEGY CCUS financé par l'UE (2019-2022), deux scénarios ont été développés et évalués économiquement pour le déploiement des technologies CCUS en Macédoine occidentale. Ces scénarios ont été créés à l'aide d'un nouvel outil logiciel pour analyser le modèle commercial CCUS dans la région grecque. Pour cela, deux sites géologiques terrestres locaux appropriés ont été utilisés pour stocker le CO_2 capturé. Cinq industries de différents secteurs industriels ont été choisies pour l'utilisation du CO_2. Des indicateurs de performance clés (KPI) ont été calculés pour mesurer la valeur à long terme et le retour sur investissement (ROI) de ce projet tout en mesurant son efficacité et sa rentabilité à court terme sur la durée de vie du processus de déploiement.

En las últimas décadas, la región de Macedonia Occidental en Grecia se ha convertido en un centro de desarrollo de la industria pesada. La captura, utilización y almacenamiento de carbono (CCUS), es una tecnología esencial para la mitigación del cambio climático, que podría aportar un crecimiento económico importante. Como parte del proyecto STRATEGY CCUS (2019-2022), financiado por la UE, se desarrollaron y evaluaron económicamente dos escenarios para la implementación de tecnologías CCUS en Macedonia Occidental. Estos escenarios fueron creados utilizando una nueva herramienta computacional para analizar el modelo económico de CCUS en dicha región de Grecia. Para esto, se eligieron dos sitios geológicos propicios para el almacenamiento de CO_2. Se seleccionaron cinco industrias de diferentes sectores productivos para la utilización del CO_2. Se calcularon indicadores claves de desempeño (KPI's), para medir el valor y retorno de largo plazo de la inversión (ROI), además de la eficiencia y rentabilidad de corto plazo, durante la duración del proceso.

1. Introduction

The latest Intergovernmental Panel on Climate Change (IPCC) report [1] provides further evidence that climate change is widespread, rapid, and intensifying with some trends now irreversible. Human-induced climate change is globally causing many weather and climate extremes. Persistent and sustained reductions in carbon dioxide (CO_2) emissions including other greenhouse gases, could reduce the greenhouse effect and improve air quality, with the expectation that global temperatures could stabilize over the next decades. In 2019, the concentration of atmospheric CO_2 reached a 2 million-year high. Furthermore, methane and nitrous oxide concentrations peaked at levels unseen in the last 800,000 years [1].

The 2015 Paris Agreement [2] aims to avoid the most devastating effects of climate change and limit global temperature increase to no more than 2°C above pre-industrial levels. The 2021 IPCC report [1] clarifies that the global surface temperature increased by 1.09°C over the decade between 2011 and 2020 compared to the period between 1850 and 1900. Additionally, the past five years were recorded to be the hottest since 1850.

Oil continues to hold the top position as the primary source of energy, accounting for 33% of the global energy mix. Moreover, fossil fuels represent 84% of the world's primary energy mix [3-4].

On July, 14, 2021, the European Commission adopted a series of legislative proposals to achieve climate neutrality in the EU by 2050. The proposals include an intermediate target of at least 55% net reduction in greenhouse gas emissions by 2030 [5]. This EU plan for a green transition, referred to as "fit for 55", consists of proposals aimed to revise and update EU legislation and is part of the European Green Deal, which outlines the EU's road-

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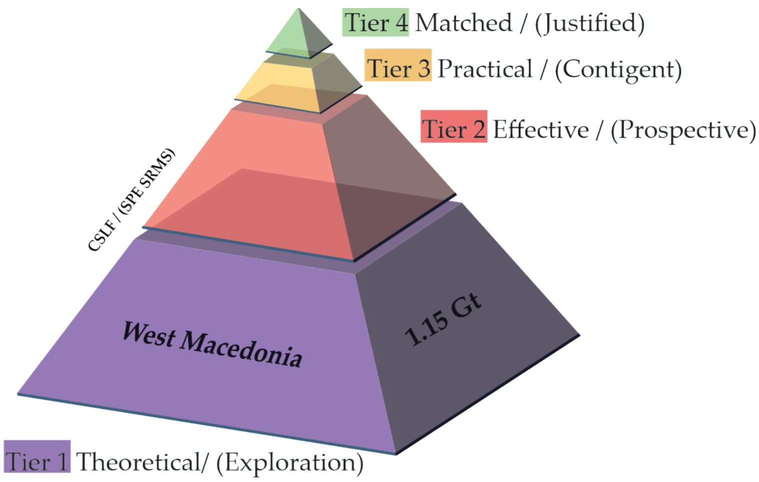

Figure 1: (A) Location of remote northern communities in Canada; (B) main geological regions; (C) climate zones; and (D) map of the studied area centered on the Arctic. YT – Yukon Territory, NWT – Northwest Territories, NU – Nunavut, NK – Nunavik, QC – Quebec and NL – Newfoundland and Labrador (Nunatsiavut).

map for a sustainable economy.

As part of its efforts, the European Union has implemented policymaking through initiatives like the Green Deal, REPowerEU and EU taxonomy. Greece, as an EU member, has committed itself to reducing CO_2 emissions to a minimum by phasing out its technologically outdated lignite-based power plants in Megalopolis and Western Macedonia.

The region of Western Macedonia is located in the northwest of Greece, adjacent to the regions of Central Macedonia (East), Thessaly (South), and Epirus (West). It shares its northern borders with the Republic of North Macedonia and Albania. The region covers a total area of 9,451 km², representing 7.2% of the country's total area and a population of 283,689 inhabitants, which is 2.6% of the country's total population.

The majority of the population (56%) lives in rural areas [6]. The capital of the region is the city of Kozani, with a population of 67,161. Other major towns include Ptolemaida with 32,142 inhabitants, Grevena with 21,440, Florina with 29,611 and Kastoria with 33,227 inhabitants [7].

The lignite industry preoccupied the workforce of these cities, causing many residents to renounce traditional activities such as farming, leading to rapid economic growth and prosperity and as a result, power plants had become the dominant sector of employment [8].

Since the early 1950s, the lignite industry has shaped the development course of Western Macedonia. The intensive exploitation of domestic lignite deposits contributed significantly to electrifying Greece and consistently supporting the security of the national energy supply. As a result, the region hosts the highest installed unit power of Greece, regarding thermal power plant units. Out of 13,077.9 MW of installed net power, the region has 3,945 MW based on lignite units and another 375 MW on hydroelectric power, covering 33% of the total capacity and 39.2% of thermal unit power. However, according to the new Greek National Energy and Climate Plan, all operating lignite-based power plants are scheduled to be retired by 2023, meaning that Western Macedonia is currently in its decarbonisation phase.

In the H2020 European Project STRATEGY CCUS (***https://www.strategyccus.eu***), two CCUS scenarios were formulated up to 2050 to evaluate the techno-economic feasibility of CCUS technologies in Western Macedonia, Greece. The main objective of this paper is to present these CCUS scenarios, the methodology used in their development, followed by a synthesis of the KPI evaluation and the main results. This techno-economic evaluation will be useful to compare the total costs, that Western Macedonia would incur by investing in CCUS technologies, to the costs incurred by the EU Emissions Trading System (ETS) in absence of CCUS projects, during the same period.

In the next subsection of this paper, an introduction to CCUS technologies is provided, followed by a description of the STRATEGY CCUS project. Section 2 includes a description of the software used and the scenario generation procedure, along with the presentation of medium-term and long-term scenarios that were developed for Western Macedonia. The third section, "Results", contains the techno-economic evaluation of both scenarios, along with pie charts depicting the benefits of CCUS adoption in the region. Finally, the concluding section presents the findings of this study on the implementation of CCUS technologies in Western Macedonia.

1.1 Carbon Capture, Utilisation and Storage technology

Currently there are only five large-scale carbon capture and storage (CCS) demonstration projects in Europe: Sleipner and Snøhvit in Norway, ROAD in the Netherlands, Iceland's Carbfix project and, Peterhead and White Rose in the United Kingdom. All these projects are offshore, storing CO_2 in deep geological formations [9].

CCUS refers to the process of capturing CO_2 and either storing it permanently or utilizing it by converting it into valuable products, such as fuels and chemicals. There are three main categories of capture technologies:

a. Post-combustion – In this method, waste gas produced by industrial combustion or power stations is captured and the CO_2 is separated.
b. Pre-combustion – This method involves pre-treatment of fuels, separating the carbon from the components that are ultimately burnt. For example, coal is first converted into a mixture of CO_2 and hydrogen by gasification, then the CO_2 is captured and only the hydrogen is burned.
c. Oxy-fuel combustion – This method involves, burning fuel with pure oxygen instead of regular air, resulting CO_2 to make up a larger fraction of the waste gas, making it easier to separate and store or repurpose the CO_2 [10].

The STRATEGY CCUS project aims to facilitate the implementation of carbon capture, utilisation, and storage (CCUS) in eight regions. These are identified as promising because they possess strategic elements, such as industrial clusters, potential CO_2 storage sites, opportunities for CO_2 utilisation and options for hydrogen production and use. The project also involves creating local development plans and business models for each region. This article expands on the previously published work "Carbon Capture, Utilisation, and Storage as a Defense Tool against Climate Change: Current Developments in Western Macedonia (Greece)" [11].

During the STRATEGY CCUS project, the potential for CO_2 storage in the Mesohellenic Trough was re-evaluated

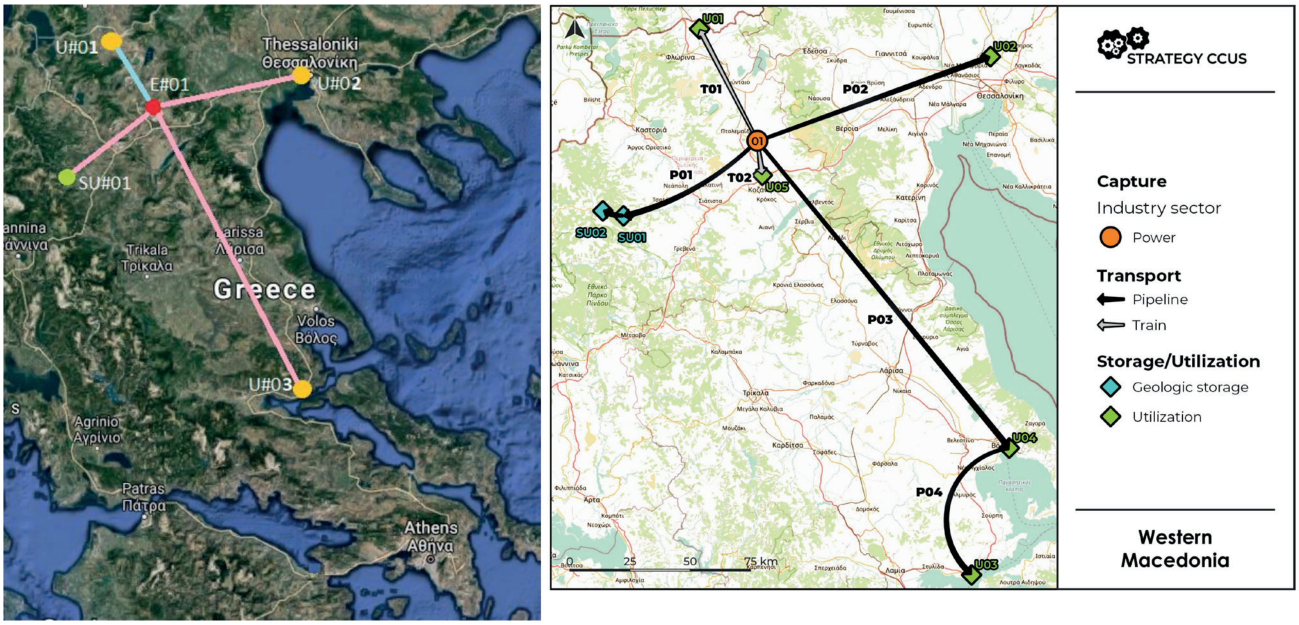

Figure 2: The transportation map for (a) the medium-term scenario and (b) the long-term scenario for Western Macedonia.

using available data whilst deploying the USDOE methodology. The Mesohellenic Trough contains the Pentalofos and Eptachori Formations, along with their corresponding daughter units. The Pentalofos Formation has an estimated CO_2 storage capacity of 1.02 Gt, whereas the Eptachori Formation can store 0.13 Gt.

Currently, CO_2 storage in Greece remains categorised with a Tier 1 status, as depicted in Figure 1. Therefore, a theoretical approach based on literature data and calculations was used to estimate the CO_2 storage capacity within sedimentary formations of the Mesohellenic Trough.

For estimating storage capacity, a four-tiered pyramid is proposed based on the North American CSLF approach [12]. The capacity quantification is based on the common P90-P50-P10 estimation (CO_2 Stored), which matures from generic formation level estimates to more detailed daughter prospects and candidate site estimates. The recommendations allow for outcomes to be transferred to an SRMS analysis.

As CCUS projects are driven by reducing global carbon emissions, the technologies employed in these projects have a critical role in achieving this goal.

2. Methods and Software (Tool)

During the STRATEGY CCUS project, a specialized software was developed to create local medium-term and long-term CCUS scenarios in each of the seven participating European countries and their eight regions. This software was developed by a core team composed of the STRATEGY CCUS project partners [13-14] using Microsoft Excel. The software is essentially an interconnected database with many different mathematical functions to describe the individual CCUS elements of Capture, Utilisation, and Storage. The software generates custom scenarios for different time horizons while performing extensive techno-economic analysis. By using this software, various economic Key Performance Indicators (KPIs) were generated, comparing the cost of implementing a CCUS project in the region of interest with the cost of paying CO_2 taxes in the same region if such a project were not implemented. For each region, two main scenarios were implemented: a medium-term scenario from 2030 to 2040, and a long-term scenario extending to 2050.

The data required for this software tool were gathered during a previous project and contain information about emitters, storage sites and industries that can utilise quantities of CO_2 in every participating country. This data created a database that was integrated into the tool, enabling the defining of business case scenarios, CO_2 hubs and clusters for each case. The basic starting point for the scenarios includes the publicly available data integrated into the tool, allowing the deployment of these scenarios.

One of the challenges facing CCUS technologies is the transport of significant volumes of CO_2 from point sources to sites established for large-scale storage. To address this issue, routing algorithms were applied with the help of GIS software to define feasible routes connecting sources, utilisation locations, and storage regions for captured CO_2. The transport routes and modes of transportation were designed and chosen accordingly to minimize the total cost. Solutions include, pipeline transportation, while train, truck or ship transportation were also available through the tool, depending on the transported volume of CO_2 and its probability of coming from dispersed sources. The study also evaluated the cost of pipeline transport, based on the quantity of CO_2 supplied and the distance, compared to CO_2 shipped by tanker vessels. The results show that the pipeline option is cheaper, but only for shorter distances. The costs for this implementation are evaluated in the CCUS scenarios below:

a. They are based on public data and directly related to stakeholders (Industry and Regional Committee).
b. They depend on the CO2 capture profile, transport options and storage capacity for Greece.
c. They involve financial assessment of each scenario by submitting Key Performance Indicators (KPIs).
d. They are harmonized with greenhouse gas reduction targets for each country.
e. They are expected to increase the likelihood of CCUS deployment in Greece, particularly Western Macedonia.

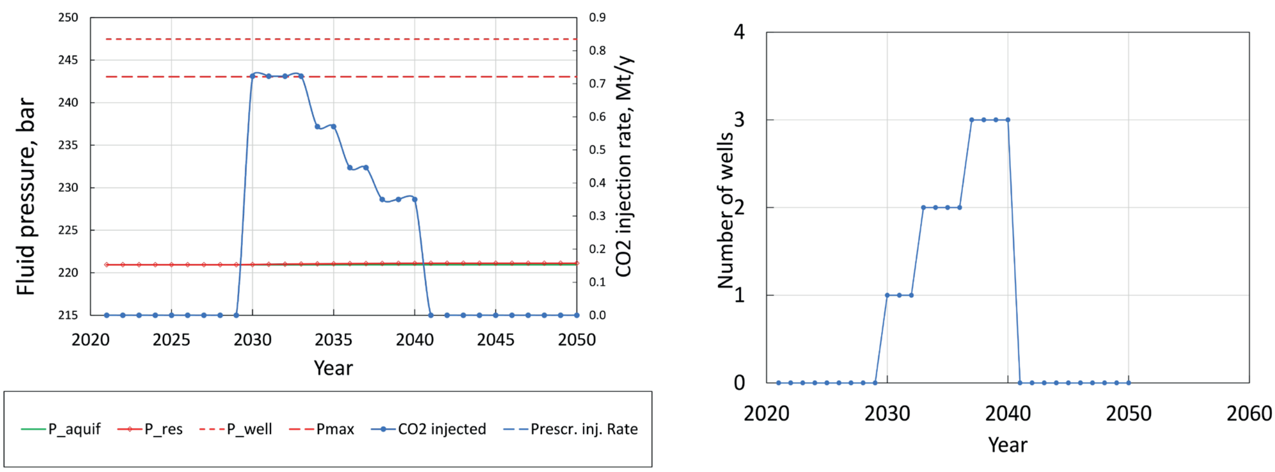

Figure 3: (a) Storage for the medium-term scenario in Western Macedonia; (b) The number of required wells in the medium-term scenario.

2.1. Description of the scenario generation procedure

The scenario creation tool identifies the linkages between emissions, transport modes, CO_2 reuse, and storage sites, to create local perspectives. It then checks the correlation between the different captured CO_2 flows, their transportation or utilisation. It also checks the potential for storage at the local level, form short-term to long-term.

For each selected regional scenario, a financial estimate has been made concerning the cost for each scenario and for each tonne of CO_2 avoided. Calculations were then made of Key Performance Indicators (KPIs) such as CAPEX / OPEX, additional energy costs, CO_2 avoidance and ETS savings. Moreover, the tool considered transport corridors on multiple time scales and then developed the most cost-effective transportation network.

The tool imported data on reservoir characteristics, as well as data on industries to be exploited for CO_2 reuse and the Ptolemaida V emitter unit. Data on interconnection points, such as spatial data, pipeline characteristics, gas temperature, and pressure were also imported by the tool.

2.2. The short/medium-term scenario for Western Macedonia

Adhering to the new Greek National Energy and Climate Plan, all currently operating lignite-based power plants will be retired by 2028. The only operational lignite power plant that will remain is the new Ptolemaida V power plant, located in North-Western Greece. The estimated CO_2 emissions available for CO_2 capture from the Ptolemaida V power plant are 4.5 Mt/y for a period of 30 years. The plant is designated as a CCS-ready facility.

The Ptolemaida V power plant will contribute to multiple levels. It will renew installed plants, owned by the Public Power Corporation, producing electricity at competitive costs by reducing lignite consumption and lowering CO_2 costs. It will significantly improve the environmental footprint and lower the cost of electricity generation. Overall, it will bring significant benefits to the Greek economy and reduce unemployment.

Four key advantages of this new power plant are the reductions of a) lignite consumption by 40%, b) greenhouse gas emissions by 40%, c) pollutant emissions by 60%, and d) particle emissions by 90%.

Due to the rapid decarbonisation phase in the last years, only one emitter, Ptolemaida V, was considered for the Greek medium-term scenario. The power plant is located approximately 8km southeast of the town (Figure 2) and the captured CO_2 will be transported via pipeline.

The selected Pentalofos Storage Unit for the medium-term scenario is located approximately 67 km west of Ptolemaida V. The first captured CO_2 utilisation site is located in Florina, a nearby city 68 km north of Ptolemaida V. The transportation of CO_2 to Florina will be done by train, using the existing railway network in this area. The second utilisation site is in Thessaloniki, the second-largest city in Greece, located 166 km from Ptolemaida V. Furthermore, the third utilisation site, chosen in this scenario, is located in Stylida, 260 km south of the Greek emitter. All transportation routes and their characteristics were generated using GIS software, with terrain factors and elevation profiles adequately considered for the pipelines. For the industries that require train transportation, the existing railroad network was utilised. Basic user input data for the tool includes the longitude and latitude of each location, the maximum CO_2 flow rate (Mt/year) and the starting/ending year of operation.

2.3. Basic design parameters and key KPIs

The basic design parameters of the three pipelines in this scenario all have the same values. However, there are differences in distance, elevation profiles and terrain factors considered for each route. The transportation of CO_2 by train, chosen for the first utilisation site (Florina), allows for the minimisation of the total transportation costs in this scenario. The wagon capacity of the train was calculated to be 240 tn. Therefore, a locomotive with three wagons is required, making a maximum of 679 trips per year to satisfy the needs of the first utilisation site. The total time required per trip, including loading and unloading of the captured CO_2 was calculated and found to be 1.12 hours per trip.

Basic design parameters for the pipelines and train transportation include Upstream pressure/temperature; Inlet pressure/transport temperature; Maximum/minimum pressure allowed; Pipeline length; Elevation difference; Start year/construction years; Discount rate; Desired outlet pressure; Wagon capacity; Number of wagons. Additionally, some of the key KPIs include Total undiscounted costs; Total CO_2 transported; CO_2 transport costs per tonne undiscounted/discounted; travel/total time per trip.

2.4. Short description of utilisation units and results

In the medium-term scenario, three utilisation units were selected. Two of which belong to the fuel category, while the other is in the pure CO_2 category. Each industry unit has Ptolemaida V (Emitter 1) as a CO_2 source, and their ramp-up percentage is based on their prospects for carbon dioxide use.

Utilisation Site No.1 (U#01):

The U#01 utilises pure CO_2 in various industrial sectors such as oil and gas, aeronautics, automotive, beverage, chemicals, waste and water management, metal, hospital care, laboratories, and research centres. In the medium-term scenario, U#01 is projected to consume 276,120 tonnes of CO_2 annually with a ramp-up rate of 45% in the first six years. Ptolemaida V, the main scenario emitter, will provide the required amount of CO_2 for this utilisation unit.

Utilisation Site No.2 (U#02):

The U#02 aims to reduce emissions from its processes with 50% by 2030, to address climate change and contribute to the energy transition. Its activities will include innovative technologies such as recycled CO_2 utilisation, renewable energy sources, hydrogen and new raw materials. Its main facilities are located in the city of Thessaloniki in Northern Greece. In the medium-term scenario, U#02 will use 543,750 tonnes of CO_2 annually, with a ramp-up rate of 28% in the first four years. Ptolemaida V, the main scenario emitter, will provide the required amount of CO_2 for this utilisation unit.

Utilisation Site No.3 (U#03):

The U#03 is a Greek industrial company with integrated operations in the agribusiness, bioenergy and food sectors. Its facilities are located in Stylida, Central Greece, which is approximately 255 km away from Western Macedonia. In the medium-term scenario, U#03 will use 309,214 tonnes of CO_2 annually, with a ramp-up rate of 31% in the year 2038. Ptolemaida V, the main scenario emitter, will provide the required amount of CO_2 for this utilisation unit.

Utilisation results and product KPIs were generated for the currently investigated medium-term scenario. From 2030 to 2040, 1.46 Mt CO_2 will be used in the pure CO_2 category and 6.45 Mt in e-fuels. The maximum amount of CO_2 will be utilised in the medium-term scenario from 2036 to 2040 due to a ramp-up in the utilisation process.

2.5. Storage

Greece offers opportunities for CO_2 storage, such as deep saline aquifers in the Greek Mesohellenic basin, as well as depleted hydrocarbon fields in the Tertiary sedimentary basins of Prinos [11]. The Mesohellenic basin and its Grevena sub-basin region offer CO_2 storage options for the Western Macedonian industrial cluster. The Grevena sub-basin, is approximately 50 km away and characterized by deep saline aquifers.

The Pentalofos Formation (Upper Oligocene-Lower Miocene epoch) which is part of the Mesohellenic basin has been selected as the storage site for the medium-term scenario. The Pentalofos Formation consists of conglomerates, followed by turbiditic sandstones and shales, with an average thickness of 2500 m and a maximum thickness of 4000 m. The formation is divided into two daughter units, Tsarnos and Kallon, which have a similar lithologic composition, comprising of conglomerates, turbiditic sandstones (occasionally coarse-grained), shales, and a porosity ranging from 7% to 25% [15]. During this project, the potential for CO_2 storage in the Mesohellenic Trough was re-evaluated deploying the USDOE methodology based on available historical data. The estimated CO_2 storage capacity of the Pentalofos Formation is 1.02 Gt.

In Figure 3a, the storage scenario for the Pentalofos Formation and the closed storage unit is presented. CO_2 injection will be at the maximum level for the first three years (2030-2033), and following these years, the amount of injected CO_2 will gradually be reduced. Additionally, in Figure 3b, the number of wells essential for the implementation of the medium-term scenario is shown.

Table 1 presents the key KPIs for the Pentalofos storage unit (GR.SU.001) in the medium-term scenario (2030-2040). Specifically, the total amount of net CO_2 that will be stored is 5.98 Megatonnes, while the total amount emitted is only 0.03 Megatonnes. The total undiscounted costs will be 25.5 million euros, while the undiscounted CO_2 cost per tonne will be up to 4.3 euros.

Table 1: KPIs for the Pentalofos storage unit in the Greek medium-term scenario.

Key KPIs for GR.SU.001, Scenario ID: EC_Scenario_1		
	Closed	Unit
NPC in year 2021 (discounted)	-8.8	M€
Total undiscounted costs	-25.6	M€
Total CO_2 stored	5.98	Megatonnes
Total CO_2 emitted	0.03	Megatonnes
Net CO_2 stored	5.94	Megatonnes
CO_2 costs per tonne (undiscounted)	4.3	€/tonnes
CO_2 store cost per tonne (discounted)	1.5	€/tonnes
First year	2030	yr
Last year of full injection	2040	yr

3. Results

3.1. Assessment for the medium-term scenario

The Western Macedonian CCUS KPIs of the medium-term scenario are presented in Table 2. This table includes the analysis of the CCS system, CO_2 volumes, and ETS allowances. In the medium-term scenario, 20 Mt of CO_2 are captured and transported, 14 Mt are utilised and 6 Mt are stored, resulting in the avoidance of 6 Mt of CO_2 emissions. The following graphs provide information about the CCUS chain regional benefits and costs for the medium-term scenario of Western Macedonia. It is clear that transportation accounts for the largest share of the total CCUS chain costs, while storage is the smallest (Figure 4a). Additionally, CO_2 sales and ETS savings generate regional revenues and significantly reduce the total costs (Figure 4b).

The application of CCUS technologies avoided about 5.9 Mt of CO_2 emissions in Western Macedonia, while the total CO_2 emitted by carbon capture is 2.3 Mt. The financial results of the medium-term scenario are presented in the figures below. Figure 5a shows the undiscounted CAPEX for Western Macedonia, which is 46.7 million euros in the capture stage, 78.1 million euros in the transport stage, and 21.2

Table 2: Region KPIs of the medium-term scenario.

Analysis of the CCS system		***Analysis of CO_2 volumes (Mt)***		***Analysis of ETS allowances***	
Total CCS value chain				*EU ETS parameters*	
CCS value chain (€/tonne CO_2 avoided)	*-25*	*Total CO_2 Captured*	*20.4*	*Price of allowances in 2025 (€/tonne CO_2)*	*70*
		CO_2 utilised	*14.4*	*Price of allowances in 2045 (€/tonne CO_2)*	*0*
Total CAPEX per block	*-12*	*CO_2 for mineralisation (perm. avoided)*	*0.0*		
Cost of Capture (€/tonne CO_2 avoided)	*-4*	*Stored*	*6.0*		
Cost of Transport (€/tonne CO_2 avoided)	*-7*	*Total emitted with CCS*	*2.3*	*Whole regional expense without CCUS*	
Cost of Storage (€/tonne CO_2 avoided)	*-2*	*Total avoided emission*	*5.9*	*ETS costs without CCUS (M€)*	*1802.8*
		BIO CO_2 captured, neg. Emissions	*0.0*		
OPEX per block	*-13*	*Total CO_2 fed into transport network*	*20.4*	*Whole region expense with CCUS*	
Cost of Capture (€/tonne CO_2 avoided)	*-5*	*CCUS national objectives*	*200.0*	*ETS costs with CCUS, remaining emissions (M€)*	*1423.4*
Cost of Transport (€/tonne CO_2 avoided)	*-8*	*Share in national objectives*	*3.0%*	*Cost of CCUS (M€)*	*150.6*
Cost of Storage (€/tonne CO_2 avoided)	*0*			*TOTAL costs with CCUS (M€)*	*1573.9*
Transport cost (€/tonne CO_2 transported)	*-4.3*	STRATEGY CCUS A viable solution for a sustainable future		*Cost difference, with minus without CCUS (M€)*	*-229.0*
Utilisation (income from CO_2 sales) (M€)	*1226.4*			*Average yearly energy need, TWh/year*	*0.71*
EUA/ETS credit savings in the region (M€)	*379.4*			*Peak energy need, TWh/year*	*1.29*
				Breakeven CO_2 price (€/tonne CO_2)	*31*
				First year of profit	*2030*

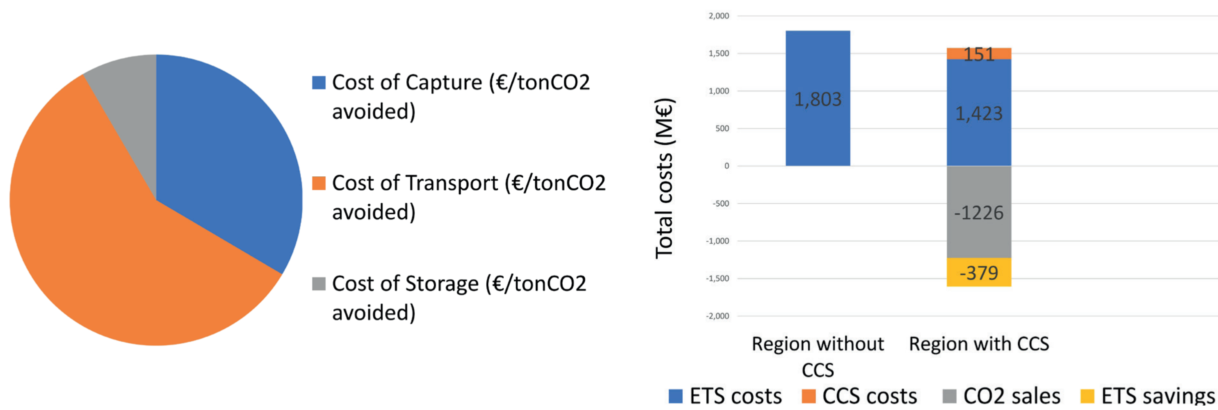

Figure 4: (a) Share of CCS total cost; (b) Total regional costs until 2040.

million euros in the storage stage. Utilisation has an undiscounted CAPEX of zero.

Regarding the undiscounted OPEX for the medium-term scenario, the utilisation procedure generates 2.71 billion euros in revenues from CO_2 sales (Figure 5b). Moreover, the total undiscounted OPEX is 162 million euros. The fraction of CAPEX (in euros) per tonne of avoided CO_2 is higher in the transport stage, whereas the utilisation stage has a value of zero (Figure 6a). The regional revenues from the CO_2 utilisation stage are unambiguous (Figure 6b). The highest fraction of OPEX (in euros) per tonne of avoided CO_2 appears in the utilisation procedure, which is due to generated revenues. On the other hand, the capture procedure incurs a higher cost per avoided tonne of CO_2.

Figure 7 displays both the project costs and income per year when implement-

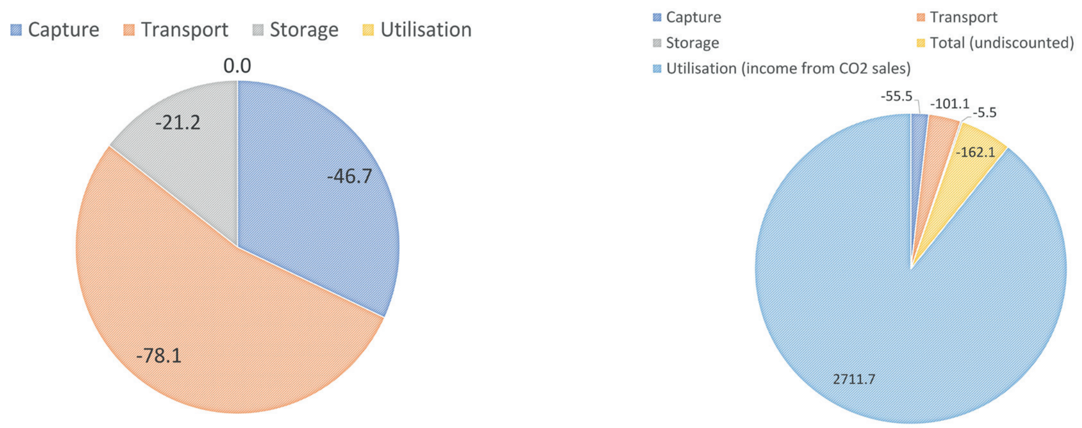

Figure 5: (a) Undiscounted CAPEX for the Greek medium-term scenario; (b) Undiscounted OPEX for the Greek medium-term scenario

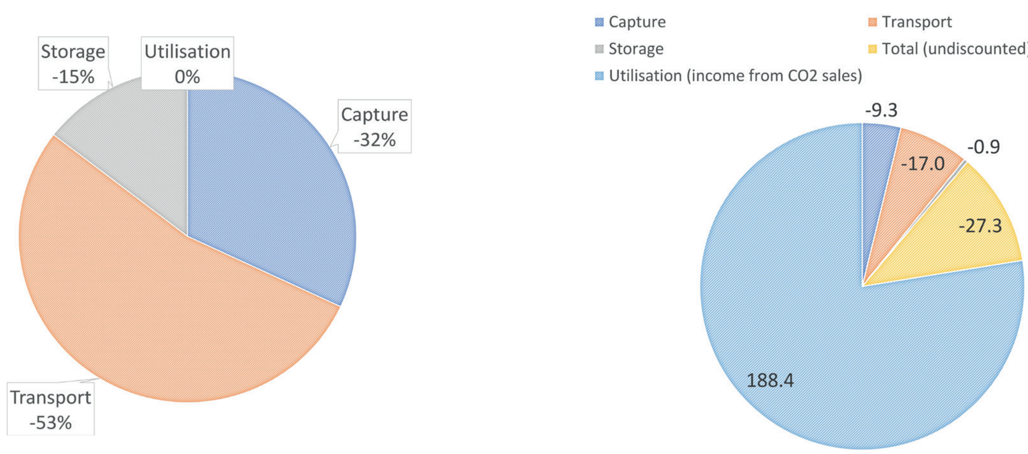

Figure 6: (a) CAPEX per avoided tonne of CO2 for the Greek medium-term scenario; (b) OPEX per avoided tonne of CO₂ for the Greek medium-term scenario.

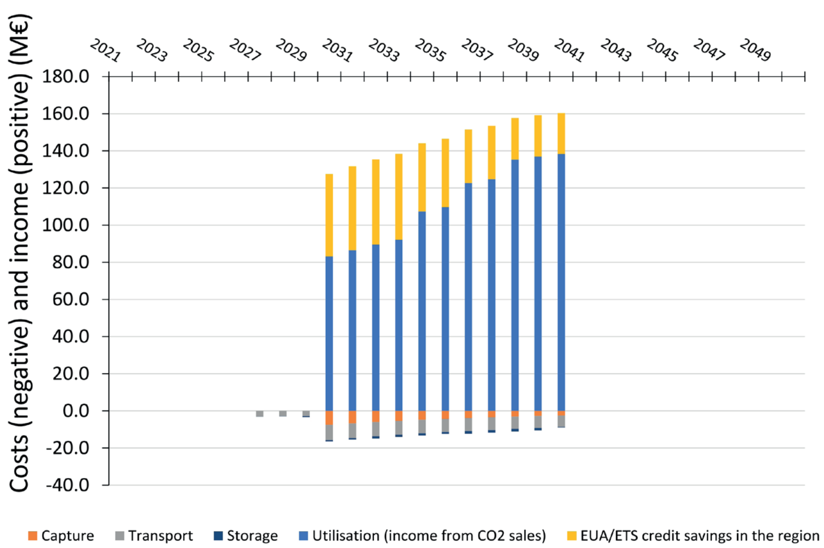

Figure 7: Regional costs and incomes for Western Macedonia in the medium-term scenario.

ing a medium-term scenario in Western Macedonia. Between 2027 and 2030, most costs will be incurred by the transport stage, followed by the storage stage. From 2030, the first year of the medium-term scenario, Western Macedonia will start earning incomes from EUA/ETS savings and CO_2 sales. Thus, the regional revenues will be significantly higher than the costs during the medium-term scenario. This indicates that the developed medium-term scenario is advantageous and profitable for Western Macedonia, both economically and environmentally.

3.2. Assessment for the long-term scenario

The primary difference between the medium-term and long-term scenarios is the duration of the latter, which is extends up to 2050. Furthermore, the long-term scenario includes five utilisation units, with the addition of one cement plant next to the Ptolemaida V unit, and another industrial company with integrated operations in fertilizers and the agribusiness. The long-term scenario also features an extra storage unit which is chosen as a second storage site, located in Eptachori village and also part of the Mesohellenic basin.

The KPIs for the long-term scenario of CCUS in Western Macedonia are presented in Table 3. This table includes the analysis of the CCS system, CO_2 volumes and ETS allowances. 39Mt of CO_2 are captured, 39Mt are transported, 32 Mt are utilised and 7 Mt are stored in the long-term scenario. The avoided emissions amount to approximately 17 Mt of CO_2.

The following graphs provide important

Table 3: KPIs for the long-term scenario in Western Macedonia.

Analysis of the CCS system		***Analysis of CO_2 volumes (Mt)***		***Analysis of ETS allowances***	
Total CCS value chain				***EU ETS parameters***	
CCS value chain (€/t CO_2 avoided)	*-36*	*Total CO_2 Captured*	*38.9*	*Price of allowances in 2025 (€/tonne CO_2)*	*70*
		CO_2 utilised	*31.7*	*Price of allowances in 2045 (€/tonne CO_2)*	*212*
Total CAPEX per block	***-17***	*CO_2 for mineralisation (perm. avoided)*	*10.0*		
Cost of Capture (€/tonne CO_2 avoided)	*-11*	*Stored*	*7.2*		
Cost of Transport (€/ tonne CO_2 avoided)	*-4*	*Total emitted with CCS*	*4.3*	*Total regional expense without CCUS:*	
Cost of Storage (€/tonne CO_2 avoided)	*-2*	*Total avoided emission*	*17.2*	*ETS costs without CCUS (M€)*	*2,672.7*
		BIO CO_2 captured, neg. Emissions	*0.0*		
OPEX per block	***-19***	***Total CO_2 fed into transport network***	***39***	***Total regional expense with CCUS***	
Cost of Capture (€/tonne CO_2 avoided)	*-13*	*CCUS national objectives*	*200*	*ETS costs with CCUS, remaining emissions (M€)*	*1,619.0*
Cost of Transport (€/ tonne CO_2 avoided)	*-6*	*Share in national objectives*	*8.6 %*	*Cost of CCUS (M€)*	*613.8*
Cost of Storage (€/tonne CO_2 avoided)	*0*			*TOTAL costs with CCUS (M€)*	*2,232.8*
Cost of Transport (€/ tonne CO_2 transported)	*-4.3*			***Cost difference, incl. minus excl. CCUS (M€)***	***-440.0***
Utilisation (income from CO_2 sales) (M€)	*2841.7*			***Average yearly energy need, TWh/year***	***0.91***
EUA/ETS credit savings in the region (M€)	*1053.8*			***Peak energy need, TWh/year***	***1.29***
				Breakeven CO_2 price (€/tonne CO_2)	*39*
				First year of profit	*2030*

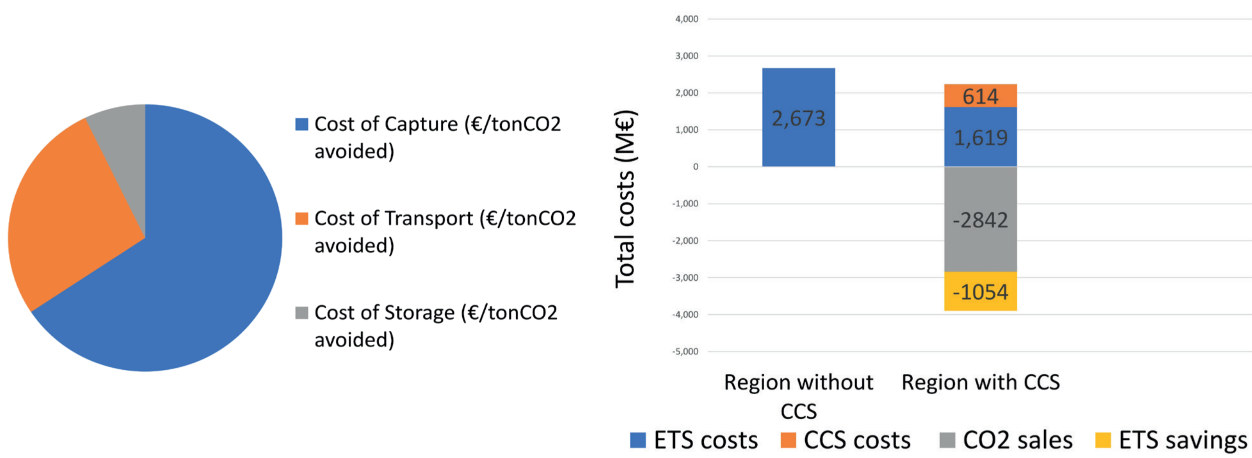

Figure 8: (a) Distribution of total cost among CCS stages; (b) Total regional costs until 2050.

information on the regional long-term scenario of Western Macedonia and are essential to evaluate. They specifically contain relevant details about regional benefits and costs of the CCUS chain. Clearly, costs of capture represent the largest share of the total costs in the CCUS chain, while costs of storage represent the smallest share (Figure 8a). Additionally, CO_2 sales and ETS savings generate regional revenues, which significantly reduce the total costs (Figure 8b). Therefore, the implementation of a long-term scenario will enable Western Macedonia to generate revenues of up to nearly 3.8 billion euros from CO_2 sales and ETS savings.

Emission benefits resulting from the application of CCUS technologies in Western Macedonia are presented in Figure 9a, showing an avoidance of approximately 17 Mt of CO_2 emissions. In contrast, only

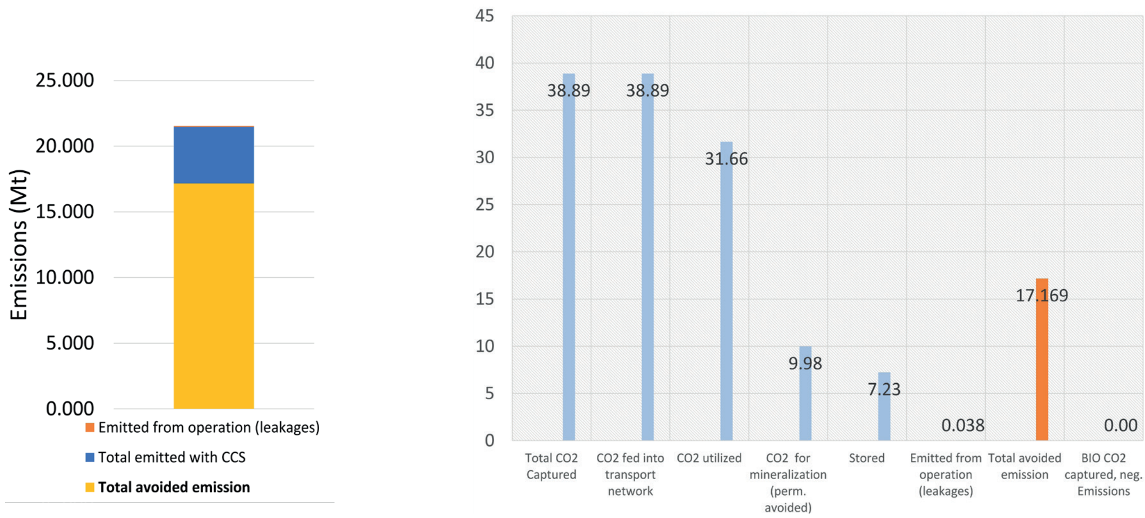

Figure 9: (a) Reduction of regional emissions until 2050; (b) CO2 flows in the long-term scenario for Western Macedonia.

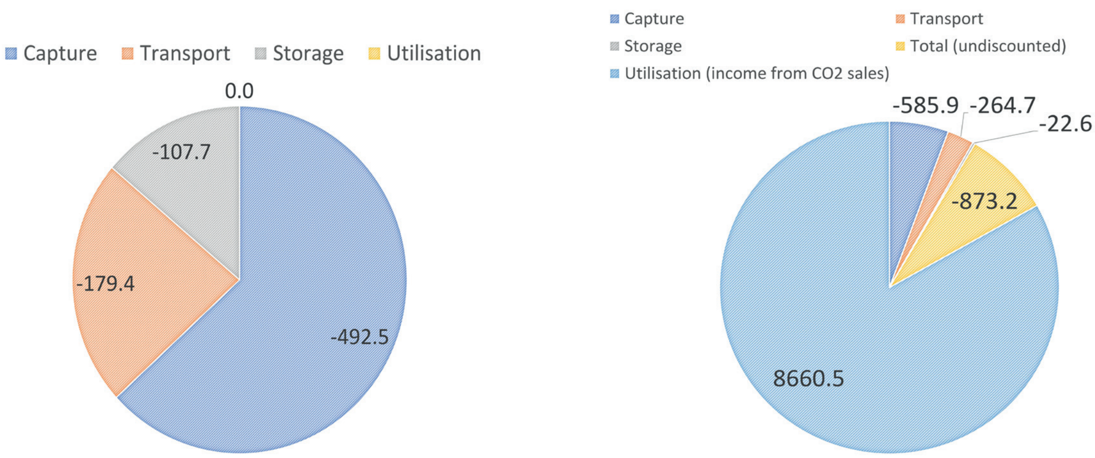

Figure 10: (a) Undiscounted CAPEX for the Greek long-term scenario; (b) Undiscounted OPEX for the Greek long-term scenario.

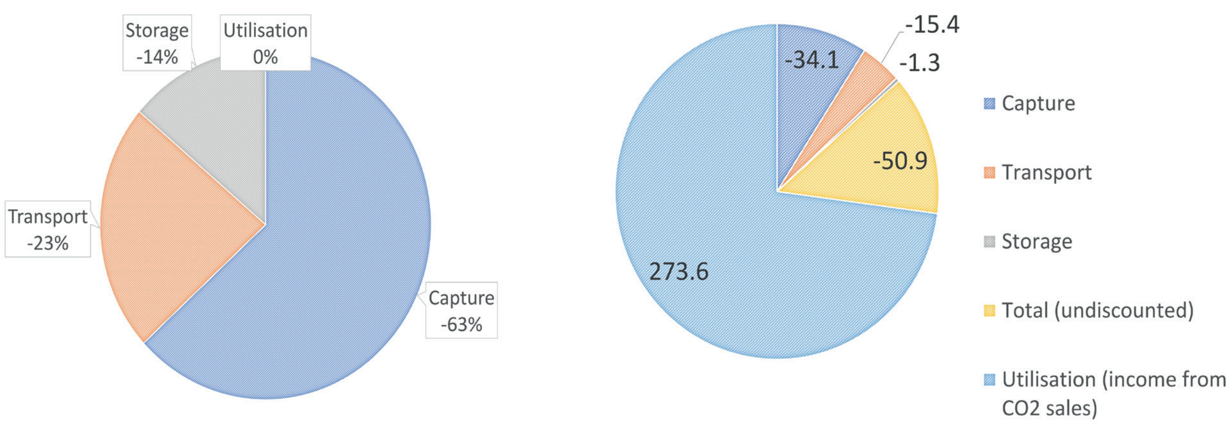

Figure 11: (a) CAPEX per avoided tonne of CO_2 for the Greek long-term scenario; (b) OPEX per avoided tonne of CO_2 for the Greek long-term scenario.

0.04 Mt is emitted by carbon capture. The results show evidence for the significant environmental benefits of CCUS technologies. Furthermore, Figure 11b provides detailed information on CO_2 flows.

The financial results of the long-term scenario are presented in the following figures. Figure 10a shows the undiscounted CAPEX for Western Macedonia's long-term scenario. The undiscounted CAPEX is 492 million euros in the capture stage, 108 million euros in the storage stage, 179 million euros in the transport stage and the utilisation has an undiscounted CAPEX of zero.

Regarding the undiscounted OPEX for the long-term scenario, Figure 10b shows that the utilisation procedure generates 8.6 billion euros in revenues from CO_2 sales. The total undiscounted OPEX is 873 million euros (586 M€ costs from capture, 265 M€ costs from transport, and 23 M€ costs from storage). The fraction of CAPEX (in euros) per tonne of avoided CO_2 is larger in the transport and capture stages, while for utilisation it appears to be zero (Figure 11a). The regional revenues from the CO_2 utilisation stage are significant (Figure 11b) and the fraction of OPEX (in euros) per tonne of avoided CO_2 is the highest in

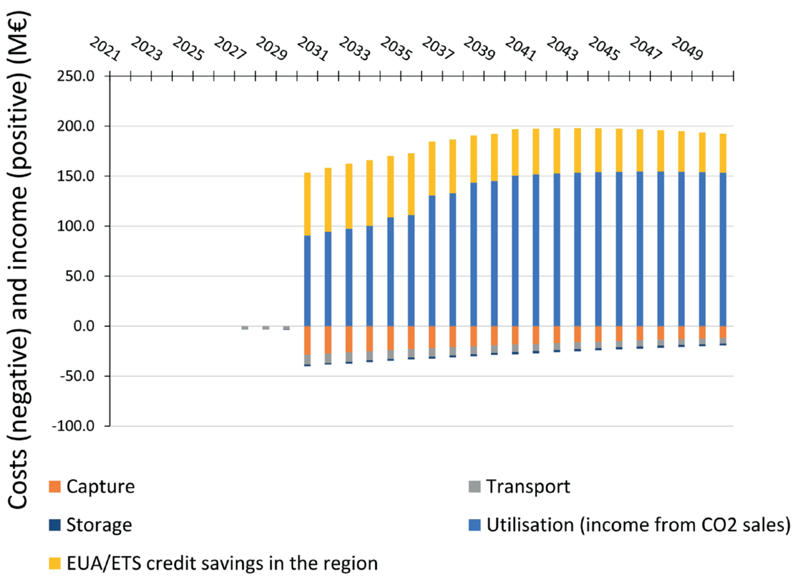

Figure 12: Regional costs and incomes for Western Macedonia in the long-term scenario.

the utilisation stage due to these revenues. In the Greek long-term scenario, the capture and transport stages are the most expensive per avoided tonne of CO_2.
Figure 12 presents the project costs and incomes for Western Macedonia per year when implementing the long-term scenario. From 2027 to 2030, the region will incur the most expenses in the transport stage, followed by the storage stage. However, from 2030, the first year of the long-term scenario, Western Macedonia will earn from EUA/ETS savings and CO_2 sales. Thus, the regional revenues will be much higher than the costs during the long-term scenario. This indicates that the developed long-term scenario is highly advantageous and profitable for Western Macedonia, both economically and environmentally.

4. Discussion - Conclusions

In the period from 2011 to 2019, the costs related to lignite activity in the lignite units of Western Macedonia decreased by about 10% per year [16]. The goal of a complete national lignite phase-out by 2028 is included in the National Plan for Energy and Climate. The commitment to phase-out lignite in power generation will lead to a radical transformation of the energy sector and achieve a climate-neutral economy. CCUS is an essential technology for climate change mitigation and can also deliver economic growth and employment. Industries such as cement, iron and steel, chemicals, natural gas, and electricity generation can benefit from the ability of CCUS to deep-cut industrial CO_2 emissions. The CCUS sector is growing at an unprecedented rate and this growth is accelerating. The economic performance of CCUS is becoming increasingly important for achieving reliant net-zero technologies. CCUS projects can stimulate the development of CCUS technologies to reach the EU's long-term climate targets at the lowest possible cost.
The development of CCUS technologies in Western Macedonia can provide a significant boost to the Greek region. The region has experienced major economic decline due the decarbonisation phase, resulting in business shutdowns and job losses. However, for both the medium-term and long-term scenarios, several benefits are brought to the region, both in economic and environmental terms. The deployment of CCUS technologies can create jobs in various sectors such as power, cement, steel, refinery, oil & gas, shipping, and the pipeline industry. For example, constructing CO_2 capture facilities, CO_2 transport pipelines, and geological storage sites can generate employment in construction, engineering, and manufacturing. Western Macedonia offers a high storage capacity, which is crucial for the development of CCUS technologies. In addition, the Ptolemaida V lignite unit, the only emitter for both scenarios, is CCUS ready, providing a significant advantage for CCUS projects. Although construction costs will be high in the first years of both scenarios, the regional revenues are expected to exceed the costs. In addition, the environmental benefits of the application of CCUS technologies in the region are clear, as a significant amount of carbon dioxide emissions would be avoided.
In addition, as part of the STRATEGY CCUS project, transnational scenarios were also developed beyond these two local scenarios. One scenario involved France, Spain, and Greece. In this transnational scenario, France and Spain participated with their carbon dioxide emitters and heavy industries for carbon capture, while storage took place in Greece due to its large geological reservoirs. Prior to storage, the CO_2 was transported by ship to the port of Thessaloniki and utilised the pipeline network of the medium and long-term scenarios. The benefits of such a process go beyond the national borders and lead to a collective approach towards the climate change problem. Countries with geological storage capacity can provide the storage aspect, while countries with large industries can cover the capture part. This interconnection between countries allows for a holistic solution to the problem and facilitates the effective adoption of CCUS technologies.

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Earth sciences at the centre of the energy transition

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Achieving a successful energy transition requires society to deploy as many technologies as possible, rather than relying on one single technology to be the 'magic bullet'. However, there are characteristics that make this transition more challenging than previous transitions in terms of its scope. These challenges include the wide range of sustainable technologies involved and the time constraints. For this research the importance of carbon capture and storage (CCS) and hydrogen technologies for the decarbonization process was analysed, including the main challenges that their large-scale implementation is facing from a subsurface perspective. The ongoing role that fossil fuels play, as well as how the hydrocarbon industry can facilitate the current transition, must also be considered. The common denominator in the analysis is the critical position of Earth sciences in discovering, characterizing, and sustainably utilizing subsurface resources. Geoscientists are essential for providing communication and cooperation between scientists and stakeholders who use, manage and preserve the subsurface. The success of CO_2 and hydrogen storage, as part of the climate change mitigation strategies, and the eventual phase-out of fossil fuels ultimately depends on the sustainable development of the subsurface.

Pour réussir la transition énergétique, la société doit déployer autant de technologies que possible, plutôt que de se fier à une seule technologie comme "solution miracle". Cependant, certaines caractéristiques rendent cette transition plus difficile que les transitions précédentes en termes de portée. Ces défis comprennent le large éventail de technologies durables impliquées et les contraintes de temps. Pour cette recherche, l'importance des technologies de capture et de stockage du carbone (CSC) et de l'hydrogène pour le processus de décarbonisation a été analysée, y compris les principaux défis auxquels leur mise en œuvre à grande échelle est confrontée du point de vue du sous-sol. Le rôle continu que jouent les combustibles fossiles, ainsi que la manière dont l'industrie des hydrocarbures peut faciliter la transition actuelle, doivent également être pris en compte. Le dénominateur commun de l'analyse est la position critique des sciences de la Terre dans la découverte, la caractérisation et l'utilisation durable des ressources souterraines. Les géoscientifiques sont essentiels pour assurer la communication et la coopération entre les scientifiques et les parties prenantes qui utilisent, gèrent et préservent le sous-sol. Le succès du stockage du CO_2 et de l'hydrogène, dans le cadre des stratégies d'atténuation du changement climatique, et l'éventuelle élimination des combustibles fossiles dépendent in fine du développement durable du sous-sol.

Lograr una transición energética exitosa, requiere que la sociedad utilice la mayor cantidad de tecnologías disponibles, más que confiar en que una sola tecnología sea la "bala mágica". Sin embargo, hay características que hacen que esta transición sea un mayor desafío que transiciones previas, en cuanto a su alcance. Estos desafíos incluyen el amplio rango de tecnologías sustentables involucradas y las limitaciones de tiempo. Para esta investigación se analizaron, la importancia de la captura y almacenamiento de carbono (CCS) y tecnologías basadas en hidrogeno, para los procesos de descarbonización, incluyendo los desafíos principales que enfrenta su implementación a gran escala, desde la perspectiva de subsuperficie. También debe considerarse el rol actual de los combustibles fósiles, y como la industria de hidrocarburos puede facilitar la presente transición. El denominador común en el análisis es la importante participación de las Ciencias de la Tierra, para descubrir, caracterizar y utilizar en forma sostenible los recursos del subsuelo. Los Geocientistas son esenciales para proporcionar la comunicación y cooperación entre los científicos e inversionistas que usan, administran y preservan los recursos de subsuperficie. El éxito para el almacenamiento del CO_2 e hidrogeno, como parte de la estrategia para la mitigación del cambio climático y la eventual eliminación de combustibles fósiles, depende en gran medida del desarrollo sustentable de la subsuperficie.

1. Geological resources drive energy transitions

The development of today's society can be measured in energy transitions [1], which have been driven by geological resources [2]. In the 17th century the prices of wood, dried manure and charcoal skyrocketed due to shortages, therefore industrialising economies like Great Britain, Belgium and France required a cheaper source of energy [3]. Coal provided a solution to this demand, marking the beginning of the first energy transition. Throughout the 18th and 19th centuries, coal's contribution to the global energy generation kept increasing. With the development of efficient steam engines, coal mines were able to go deeper, providing more production power and raw materials to support the growing industry. Consequently, significant technological advances were made, and innovative uses of coal were developed [4].

The second energy transition began in Pennsylvania, USA, in the mid 19th century when the first commercial oil well was drilled. It was not until a century later, during World War II, that oil production took off in response to the high demands of the transportation sector. Natural gas was not far behind when inventions such as the Bunsen burner and pipelines began to incorporate this resource into house-

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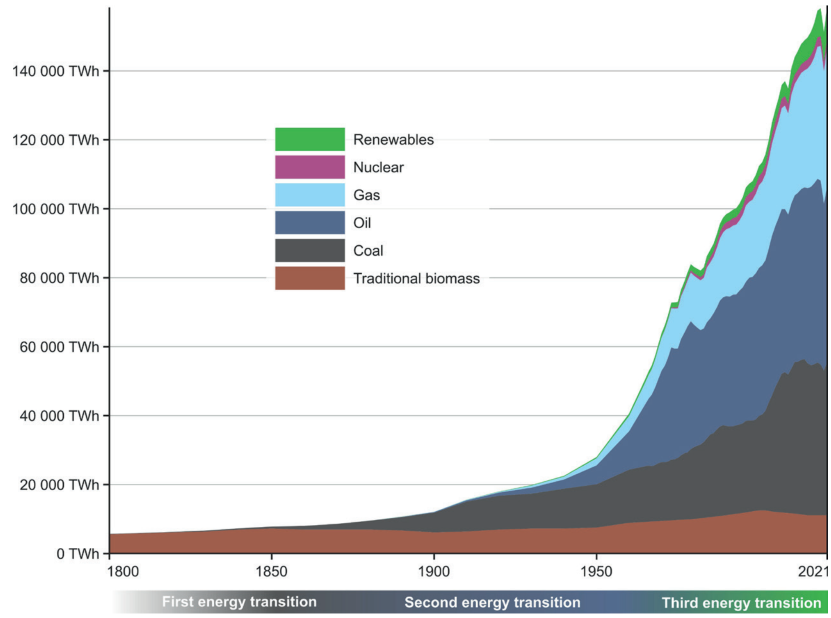

Figure 1: Global primary energy consumption, by source [7]. During the first two energy transitions increase in fossil fuels use is clearly visible. The third, energy transition is only marginally visible at global scale. This indicates both the urgency of action and despite all efforts, the significant role that fossil fuels will maintain in the coming decades.

holds and other appliances [2]. At the beginning of the 21st century, approximately 80% of the total global energy consumption was generated from fossil fuels, with oil being the dominant resource, followed by coal and natural gas. This means that, despite having replaced wood with coal and then coal with oil and gas, we have relied on hydrocarbons for over 160 years (Figure 1) [1], [5].

According to the World Economic Forum, the current and third energy transition consists of transforming our energy systems into more efficient and environmentally friendly systems while still guaranteeing economic growth, energy security and energy access. This transition was initiated by the Paris Agreement and its urgent need to reduce greenhouse gas emissions, an effort that has legally bound 194 countries [6].

However, the current energy transition is substantially different than the previous ones for several reasons. Firstly, the current energy transition is goal-oriented, meaning that it is intentional and being realised to address persistent environmental issues, whereas the previous energy transitions were emergent, meaning that they were enabled by new opportunities and technologies. The aim of the current transition is to mitigate climate change for the 'common good', but there is little to no incentive for private actors to undertake this transition. This is exacerbated because sustainable energy technologies often do not have immediate user benefits compared to traditional technologies and are usually less cost-effective. As a result, sustainable technologies will only be able to replace incumbent systems with the help of changes in economic conditions such as taxes and subsidies [8]. Thirdly, society's use of hydrocarbons extends beyond its energy needs, to the production of thousands of everyday products that have shaped our consumption (and disposal) habits for decades. In Europe, the circular economy action plan was adopted in 2020 with the goal of reducing waste to a minimum and to reduce the dependence on raw materials. This would result in more reliable, sustainable products that can be reused, upgraded and repaired, which in turn would decrease energy and resource consumption. However, these practices are, by nature, contradictory to the overall consumerist systems of our world [9]. Finally, there is the time constraint. The previous energy transitions took at least a century to fully adopt new energy sources across all industries and aspects of daily life. However, to meet the climate targets of the Paris Agreement we need to reduce fossil fuel emissions in less than half of that time [10].

Considering the above, a portfolio of measures is required, including renewable energy sources, more efficient production processes, changes in lifestyles, and other emissions reduction technologies. Like previous energy transitions that were driven by geological resources, the current transition will be driven by how we explore, exploit, manage, preserve and inform about the subsurface. This can be perfectly exemplified with carbon dioxide capture and storage (CCS) and hydrogen storage. Although both will have a very different place in a decarbonised society, they both rely on the geology of the deep subsurface to store hydrogen temporarily or carbon dioxide permanently. This paper analyses their importance for a society that aims to decarbonise its footprint and evaluate the main challenges that their large-scale implementation faces. This analysis reveals that even though both examples are often presented as technological or engineered breakthroughs, their success ultimately depends on geological advancements.

2. CO_2 storage capacity

CCS is an emissions reduction technology that has been proven technically and commercially successful for over two decades. At the single field scale, the technology is mature, with well-established processes for appraisal, operation and plume monitoring [11]. Currently CCS is already reaching a scale of megatonnes of CO_2 stored annually and it is anticipated to reach gigatonnes by 2050, an unprecedented scaleup in the history of energy transitions [10], [12]. Unique to CCS is the potential of reaching so-called negative emissions, when combined with biofuels or direct air capture.

Several political, legal, economic and social barriers are still hampering the large-scale deployment of CSS. Substantial obstacles include the lack of financial incentives from governments, clear legal frameworks, public concerns and opposition [13], [14]. Another relevant barrier is data availability and the characterisation and modelling of the geological storage complex. Until now, the two reservoir types that have been commercially used to store CO_2 are saline aquifers and depleted hydrocarbon fields. The former have the largest global storage potential but the least characterised properties, especially in regions where there are no hydrocarbons found [15]. According to the latest annual assessment, the global storage resources (potential) stand at 14 000 Gt of which approximately 2700 Gt are needed to meet the most ambitious climate targets stipulated by the IPCC [12], [16]. These estimates do not include the storage potential of CO_2 by mineralisation in basaltic bedrock. CO_2 storage through mineral carbonation is an emerging technology whose implementation is still limited to laboratory- and field-based experiments. Yet, the CO_2 storage potential in sub-oceanic basalts is significantly higher than the CO_2 that would be released by burning all hydrocarbons on Earth [17].

When the Storage Resource Management System (SRMS) is applied to the global storage potential (14 000 Gt), less than 0.002% corresponds to 'commercial projects', 4% is classified as 'sub-commercial' and the remainder (96%) falls into 'undiscovered resources' [16], [18]. The latter consists of areas where the geology is known but no targeted data well has been drilled to further characterise the reservoir. The maturation process of such 'undiscovered' resources can take up to a decade, from which 2 to 4 years are spent for the site screening, selection and characterization [11], [19], [20]. Cavanagh et al. (2020), discourage the application of the SRMS, as it suggests having a bias towards depleted hydrocarbon fields, and thus undermining the potential of saline aquifers. Additionally, Akhurst et al. (2021) emphasise the importance of the first reservoir appraisal phases when maturing a storage resource [10]. For early stage 'undiscovered' storage units, the SRMS fails to reflect the level of understanding and confidence of capacity and containment. The lack of classification details and the high maturation bars of the SRMS would be of limited value if the goal is to develop storage resources to bankable reserves that can meet the climate mitigation targets in time. Geoscientists working on the appraisal of CO_2 storage resources play a key role at these early stages, as they are crucially involved in data acquisition and interpretation that are fundamental to maturing the storage resource. Even in the development of new and more universal resource classification systems such as the UNFC (United Nations Framework Classification for Resources), geoscientists are at the centre due to their understanding of the subsurface [21].

3. Public perception of on- and offshore CO_2 storage

Considering the high road ahead, geological storage of CO_2 needs to be explored in as many reservoir types as possible and both at offshore and onshore locations [22]. However, until now offshore storage sites are preferred mainly because they face less resistance from the public [23], [24]. In the case of Europe, the North Sea has the primary focus for CCS in most surrounding coastal countries, as it is the region with the largest identified storage potential so far [24], [25]. The extensive and longstanding hydrocarbon extraction activities in the North Sea also made it a logical region of interest given the data availability, existing infrastructure and overall experience with the subsurface.

Deploying onshore storage offers important advantages compared to offshore storage, such as significant reductions in transport and potential storage costs, local management of CO_2 emissions from nearby sources and its contributions to local economic development [22], [26]. Despite these advantages, the development status of onshore storage in Europe remains at pilot and laboratory tests [24], [27]. Aside from economic and regulatory aspects, public opposition and lack of political support remain the biggest challenges for enabling onshore storage. This is confirmed by several failed onshore storage projects (either cancelled or reduced in scope) in the United States, Germany, The Netherlands, Ireland and the United Kingdom, mainly due to societal opposition [28]–[32]. These examples make it clear that in order to make onshore storage a reality, it cannot be tackled in the same way as offshore storage. Early, open and transparent public engagement campaigns are necessary as well as enabling communities to have a say on CCS implementation in their areas through inclusive in-depth discussions. A multi-dimensional approach to engaging with the public is strongly advised as not all communities are homogenous [13], [28], [33].

Two of the biggest public concerns are related to induced seismicity and CO_2 leakage. Successful onshore storage projects in Germany and Algeria have paid special attention to risk management, both to monitoring methods and its corresponding public communication activities. One of the biggest lessons learned from the In Salah demonstration project in Algeria is the importance of tailoring the package of monitoring methods to address site-specific leakage risks identified in the initial stages. This package should, however, remain sufficiently adaptable for the operational phase [15], [34]. Additionally, leakage risk assessments were made after a faster-than-expected CO_2 flow between wells was identified, that could ultimately leak into potable groundwater and the natural gas cap. While the risk was estimated to be low, corresponding safety measures and responses in case of an actual leakage were evaluated and recommended [35]. From the injection pilot site at Ketzin in Germany, experience has shown that the monitoring should be as interdisciplinary as possible, including geophysical, geochemical and microbial methods that cover different time and spatial resolutions [27]. With respect to the regulations dealing with site closure, transfer of responsibility to the competent authority and post-closure obligations, the Ketzin injection project has found that the criteria stated by the EU CCS Directive are restricted to high-level (vague) conditions. Requirements regarding long-term stability, leakage and conformity of modelled and observed behaviour are imposed without providing specific technical criteria based on real site performance data, which can also demonstrate satisfactory long-term site performance [27], [36].

Given the importance of the risk management plan for the site abandonment and responsibility transfer, communicating the risks and the risk management and monitoring plans is as important as understanding them. The operators of the storage site, who should involve geoscientists, need to have an effective, clear communication with the competent authority and the public when demonstrating the fulfilment of long-term site stability criteria. In turn, successful communication will earn more support from regulators, policy makers and the government in general [15], [36], [37].

4. Geological storage for the hydrogen economy

The use of hydrogen to decarbonize the power and industry sector is becoming a key priority in achieving the energy transition in many parts of the world. Its many applications across the industry and the fact that it can be used as energy carrier and storage buffer without emitting CO_2 when used, show its huge potential [38]. Hydrogen has been produced and used for different applications for over two centuries. In Europe, less than 2% of the energy consumption is in the form of hydrogen and it is mainly used as feedstock to produce chemical products [39], [40]. Despite hydrogen being the most abundant element in the universe, on Earth it is mainly found bound to other atoms, including organic compounds. Most of the hydrogen gas produced today is extracted from fossil fuels like natural gas and coal. Thus, in order to consider hydrogen as a clean commodity or energy, one must take its production pathway into account [41].

Hydrogen can be formed using renewable electricity and electrolysis, which involves splitting water into hydrogen and oxygen. However, the efficiency of this process is still very low, which limits the deployment of this technology at industrial scale [42].

The more renewable energy contributes to the energy systems, the greater the need will be to deal with the variable and intermittent nature of these renewable sources. The energy storage potential of hydrogen has been put forward as highly beneficial to deal with these issues and therefore, improves the flexibility of renewable energy systems, by storing surplus renewable electrical energy for longer periods of time [39], [43]. Given that hydrogen has good energy density by weight but poor energy density by volume compared to hydrocarbons, larger storage sites are required to store it. Similarly to methane and carbon dioxide, hydrogen can be stored in the subsurface. Although the reservoir properties needed to store hydrogen do not differ much from the ones needed to store methane or CO_2, the behaviour of hydrogen underground is considerably different and still not completely characterised. Examples of reservoir types suitable for hydrogen storage are aquifers, depleted hydrocarbon fields and mined salt caverns [44]. The storage technology has already been proven to be safe by different companies in the UK, US and France. Deploying such technology at commercial scale is still largely under development. Thus, the experience gained from carbon dioxide and methane storage is being exploited to accelerate this development [45]–[47].

While there are legal and economic constraints that still need to be solved, most of the challenges and knowledge gaps lie in the understanding and characterisation of the geological storage complex before, during and after the hydrogen is stored. Site selection criteria, risks of pipeline embrittlement, microbial activity and conversion, use of alternative cushion gases, hydrogen losses and leakage, and the monitoring and understanding of the flow, containment and hysteresis of hydrogen are the most important issues to tackle [11], [48], [49].

5. A future for fossil fuels?

As discussed before, the current energy transition has time constraints when it comes to complying with the Paris Agreement. According to the latest IEA assessment, the world is not on track to meet the below 2°C scenario. In 2021, coal accounted for one third of the global electricity generation. Despite pledges from governments to phase out coal, global CO_2 emissions from coal-fired power plants also grew to a record high. The COVID-19 pandemic and the Ukrainian-Russian conflict has caused several European countries to relax coal-fired production measures, resulting in phase-out delays [5]. Compared to the year 2000, the share of fossil fuels in the global energy consumption has only decreased from 86.1% to 84.3% in 2020, of which 33.1% corresponds to oil, 27% to coal and 24.3% to gas [7].

While these figures do not exactly align with the energy transition's overall goals, phasing out of fossil fuels is a more complex process than adding generation capacity from other energy sources. Significant investments are also required in infrastructure, raw materials and energy storage, along with substantial adaptations in our energy consumption habits [1], [50]. As a result, fossil fuels will still be needed for the coming years, if not decades, to maintain the supply and demand in balance until the shift to a decarbonised energy system is completed. At the same time, investments and efforts into renewable energy sources and storage need to scale up quickly to effectively reduce the demand on hydrocarbons [51].

There are several strategies that enable the hydrocarbon sector to have an active and supporting role in the energy transition. First off, current and future hydrocarbon production is required to shift its focus to low carbon intensity hydrocarbons and improve the efficiency of the production processes. Poorly performing reservoirs that require specific interventions or higher well density, for example, demand additional expenditure of energy per unit of hydrocarbon produced, resulting in a higher carbon footprint of the production process. Successfully quantifying and characterizing the geological complex is then crucial to relate it to the upstream CO_2 emissions [52]. Other examples of efficiency improvements include minimizing flaring of associated gas and venting of CO_2 or using CCS in refining [53]. Secondly, enhancing hydrocarbon production with CO_2-EOR/EGR (CO_2-Enhanced Oil Recovery/Enhanced Gas Recovery) can significantly reduce the carbon footprint, while providing a business case kickstart for CO_2 storage [54], [55]. Geopolitically, this also enables greater independence of foreign hydrocarbons that likely have a larger environmental impact. Thirdly, the extensive experience and geological data that the hydrocarbon sector has gained over the decades can play a crucial role and accelerate the deployment of underground CO_2 and hydrogen storage. This can be achieved by utilizing depleted oil or gas fields for storage, using available data (e.g. well, reservoir simulation) to reduce uncertainty levels or simply transferring knowledge and skills that enable the maturation of a prospective storage site [11], [20], [53].

Similarly, repurposing the existing offshore infrastructure, when possible, significantly minimises capital costs and delays decommissioning costs. In the case of CCS and hydrogen storage, repurposing existing production systems is possible but entails challenges associated with capacity limitations and state and availability of the infrastructure. Further research is needed to de-risk potential projects and achieve a rapid implementation of these technologies [56], [57].

Furthermore, considering that the oil and gas industry accounts for over one third of the overall spending on emissions reduction technologies such as CCS, the hydrocarbon industry plays a key role in helping CCS and hydrogen storage to reach maturity. The resources and skills of the hydrocarbon industry can be used to partner with governments and crucial stakeholders to create viable business models, which can attract the hardest-to abate sectors [51], [53]. In the case of hydrogen, the production of hydrogen from fossil fuels paired with CCS (blue hydrogen) and the appraisal and subsequent use of reservoirs, like depleted hydrocarbon fields, for underground hydrogen storage are two important steps towards the large-scale deployment of this clean energy technology [39].

6. Linking climate and subsurface challenges

While there are various technologies and measures that allow us to decarbonize our society, these technologies cannot be regarded as isolated entities or solutions. Instead, they are integrated into a complex societal context where institutional, cultural and organisational systems are intertwined with each other [58], [59]. These systems and the actors taking part in them are what sets the pace, ease and direction of the current transition.

Furthermore, the implementation of the technologies enabling the energy transition coupled with other subsurface activities will be directly translated into a

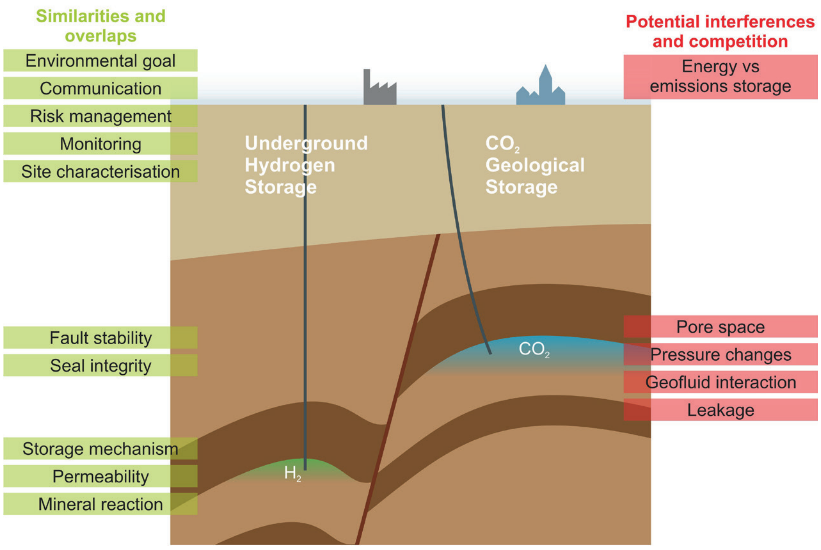

Figure 2: Underground Hydrogen Storage and CO₂ Geological Storage exhibit many similarities and overlap, both at the surface and in the subsurface. This is interesting from research perspective, but it can lead to interference and competition. Examples include competition for pore space and possible interaction between the stored fluids. In case of limited funds and/or space, a choice arises between storing emissions or energy as an emission reduction technology.

significant increase in subsurface exploitation. Activities such as groundwater extraction, disposal of high-level nuclear waste, coal mining, shallow and deep geothermal energy, CCS, Underground Hydrogen Storage (UHS), natural gas storage, and EOR/EGR are all subsurface activities that exemplify this increase in exploitation. However, the governance of the subsurface is currently highly fragmented and decentralized, typically operating under the 'first come, first served' principle. Actors and companies access the subsurface strictly considering the subsurface activity in question, without regards of other subsurface uses or resources. This kind of approach is highly inefficient, as it fails to prioritize geological structures and subsurface activities and increases the risks of long-lasting impacts on the subsurface. As a result, fair intra- and intergenerational distribution and sustainable development is compromised [60], [61]. In addition, claims or permits on other subsurface resources and activities within the same area may be subjected to adaptation measures that are often costly or that render the project unfeasible [62].

The sustainable management of the subsurface is a concept that remains insufficiently understood and underdeveloped, due to the high complexity of dealing with time and space scales, coupled with intrinsic uncertainties and the multifunctional nature of the subsurface [59], [60], [63]. On the one hand, the spatial heterogeneity of the physical and dynamic properties of the rocks dictate flow, storage, biochemical and geochemical processes, that also occur at pore, formation and basin scales [63]. Moreover, rock strata require additional geochronological analysis to understand their depositional, formation and deformation history, which contribute to a geological model that provides further information on the resource quality and the processes mentioned above. On the other hand, the multifunctional nature of the subsurface requires an extensive understanding of the interaction between different subsurface uses, the risks of such interactions and their impacts on the environment, resources, potential future subsurface activities, and the needs of present and future generations [59].

As such, the understanding of the subsurface geosystem plays a crucial role when setting above-ground goals, interactions and development probabilities. As the transition moves forward, conflicts of interest for subsurface resources will increase and there will be more situations where multiple stakeholders have an interest in a subsurface volume where there are multiple potential activities available [62], [64], [65]. The two activities in our analysis, CO_2 and hydrogen storage, exemplify this competition perfectly. Both operations are very similar, often targeting the same strata for their capacity, permeability and containment potential. They also serve the same greater purpose in addressing climate change. As a result, both technologies are complementary in the energy system, but competitive in the subsurface (see Figure 2). This example does not include potential conflicts with deep geothermal energy, a subsurface activity that plays an equally important role in the energy transition. Nowadays, the outcome of situations where there is subsurface potential for CCS, UHS and geothermal energy is steered by power struggles, vested interests, economic impacts and public pressure, whether negative or positive [60]. The creation of synergies is then necessary to foster cooperation and communication, which in turn will support decision making, prioritisation, capital allocation and addressing public concerns. A multidisciplinary framework with criteria and indicators based on the understanding of the subsurface and the surface needs, is essential for organised and coordinated governance of the subsurface ensuring its efficient, sustainable, fair and safe use [59], [66], [67].

Currently the lack of flexibility, adaptability and clarity of permitting and legal frameworks, as well as financial incentives and risk management support, pose a critical obstacle to scale up technologies such as CCS and UHS [48], [68], [69]. Likewise, incumbent systems and outdated perspectives that perpetuate carbon-based or unsustainable infrastructure and technologies, can hinder innovation and competitiveness of sustainable alternatives [70], [71]. The practices and perspectives above also affect the perception of the public by either failing to address and resolve their concerns or by promoting carbon-based lifestyles and consumption practices [37].

It is evident that the current energy transition will require a socio-technical transition where the incumbent systems, actors and increasing exploitation of the subsurface are not mutually exclusive challenges. Instead, the overarching challenge lies in reconciling and coordinating the subsurface (geosystem) resources with the above-ground sustainability and decarbonization goals while ensuring environmental equity and justice [59].

7. Geoscientists at the heart of the solution

Looking at the bigger picture and moving beyond the scope of phasing out fossil fuels, the success of the current energy transition is dependent on turning the attention towards the subsurface more than anything else. Understanding the geosystem beneath us, is essential to deploy the technologies required to decarbonize our energy systems, preserve the resources needed to continue societal development and ultimately achieve sustainability (see Figure 3).

The skills, tools and knowledge that geoscientists have, are thus present at every step of the transition. Geoscientists are needed from the very beginning to characterise the subsurface, estimate storage capacity potentials, and describe and understand the interferences between the different subsurface activities, while managing geological uncertainty. Despite the abundance of data, uncertainty can never be completely eliminated, but it should be properly characterised and accounted for in simulation tools [72], geophysical methods and well logging. When there is data scarcity, geoscientists can still use priority ranking strategies for poorly known reservoirs that carry large uncertainty. By ranking the exploration priority of such reservoirs, stakeholders can focus research and exploration initiatives [73].

Considering the high heterogeneity of the subsurface and the different dynamics taking place above-surface, geologists face an important challenge: proper training. The current and upcoming generation of geoscientists should be familiar with a wider spectrum of disciplines, including techno-economic, managerial and communication skills, which will enable them to perform their supporting role better. This includes the capacity of creating synergies for interdisciplinary cooperation. Similarly, the transfer of knowledge and skills on different geological settings and resources, and between organisations and companies across the globe, is also vital to fostering quality training of present and future Earth scientists.

Storage capacity estimations, along with reservoir characterisation are two important steps in maturing a prospective resource. Frameworks such as the United Nations Framework Classification for Resources (UNFC) and the SRMS are necessary tools to achieve a standardisation and harmonisation of definitions and criteria when assessing a resource. Having common and globally applicable standards ensures the availability of reliable, updated and understandable information on resources. Thus, the use of these frameworks enables the proper allocation of the stage of development of a resource and its quantities. Based on that, stakeholders can decide to proceed with permitting, investment and exploration and extraction activities [18], [21].

Highly dense geological information must be processed and interpreted by geoscientists to develop principles, criteria and measures which stakeholders can use to manage subsurface resources. Here, geoscientists play a critical role in decision support and risk management, not only by having the responsibility to deliver the information but also to communicate it clearly and efficiently. As the experts in the subsurface, geoscientists serve as the communication and cooperation interface (GCCI) between resources and stakeholders, with any form of power, influence, interest, opinion or concern over the subsurface. Geological Surveys Organisations and their alliances such as the Geological Surveys of Europe (EuroGeoSurveys), are geological knowledge hubs and as such are in adequate positions to serve as GCCIs. These expert hubs can also function as communication channels for the public, facilitating inclusive, open, transparent and neutral discussions about the subsurface and addressing any concerns.

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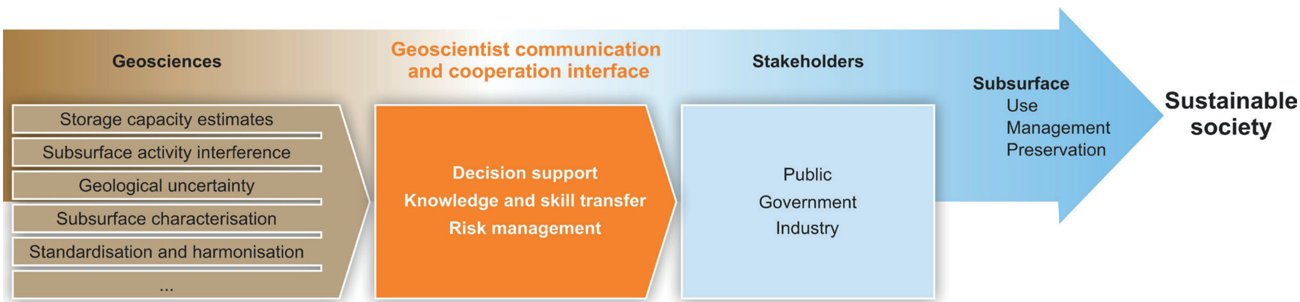

Figure 3: A sustainable society requires a sustainable use, management and preservation of the subsurface by the actors involved. Geoscientists play a central role in linking subsurface knowledge with stakeholders. They should be involved in decision support and risk management, and the transfer of knowledge and skills which is necessary to inform stakeholders correctly, maximise efficiency and create awareness. The geoscientist communication and cooperation interface serves as an essential link between the resource and its application.

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Climate change challenges and state fragility in the water, energy, food/land, raw material nexus and the position of hydrogen and Carbon Capture Utilisation and Storage for increasing resilience

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Over the last decade, Europe has experienced a sharp increase in infrastructure expenditure due to the severe and frequent natural phenomena related to climate change. Local consequences, such as habitat destruction, finite freshwater availability and food scarcity exert significant pressure on the available ecological space. Therefore, there is a growing interest in assessing risks and vulnerabilities to climate change, which has already led to a wide range of impacts on environmental systems and society, including destabilising security. Increased environmental, social, and financial damage costs are expected in the future. Many of these imminent or ongoing challenges are related to the overexploitation of resources and the energy transition, requiring a more holistic approach to encouraging new technologies, that involves a whole-of-society approach and stakeholder participation. State-of-the-art CCUS and hydrogen energy technologies, offer sustainable solutions to mitigate the current situation, allowing a reduction in carbon emissions, a transition towards a low-carbon economy, and an increased overall resilience of the international community to climate change.

Au cours de la dernière décennie, l'Europe a connu une forte augmentation des dépenses d'infrastructure en raison des phénomènes naturels graves et fréquents liés au changement climatique. Les conséquences locales, telles que la destruction de l'habitat, la disponibilité limitée d'eau douce et la pénurie de nourriture exercent une pression importante sur l'espace écologique disponible. Par conséquent, il existe un intérêt croissant pour l'évaluation des risques et des vulnérabilités au changement climatique, qui a déjà conduit à un large éventail d'impacts sur les systèmes environnementaux et sur la société, y compris la déstabilisation de la sécurité. Une augmentation des coûts des dommages environnementaux, sociaux et financiers est attendue à l'avenir. Bon nombre de ces défis imminents ou en cours sont liés à la surexploitation des ressources et à la transition énergétique, nécessitant une approche plus holistique pour encourager les nouvelles technologies, qui implique une approche de l'ensemble de la société et la participation des parties prenantes. Les technologies de pointe en matière de CCUS et d'énergie basée sur l'hydrogène offrent des solutions durables pour atténuer la situation actuelle, permettant une réduction des émissions de carbone, une transition vers une économie à faible émission de carbone et une résilience globale accrue de la communauté internationale au changement climatique .

En la ultima década, Europa a experimentado un fuerte aumento en el gasto de infraestructura debido a fenómenos naturales severos y frecuentes, ocasionados por el cambio climático. Efectos locales, tales como destrucción del hábitat, disponibilidad finita de agua fresca y escasez de alimentos, ocasionan una presión importante sobre el espacio ecológico disponible. Por lo tanto, hay un interés cada vez mayor en evaluar los riesgos y vulnerabilidades asociados con el cambio climático, que han llevado a un amplio rango de impactos en sistemas ambientales y de la sociedad, incluyendo la desestabilización de la seguridad. En el futuro, se espera un aumento en los costos por daños ambientales, sociales y financieros. Muchos de estos desafíos inminentes o actuales, están relacionados con la sobreexplotación de recursos y la transición energética, lo cual requiere un enfoque mas holístico para promover nuevas tecnologías, que involucren un enfoque de "toda -la-sociedad" y la participación de inversionistas. Tecnologías de ultima generación en los campos de CCUS e hidrogeno, ofrecen soluciones sustentables para mitigar la situación actual, permitiendo una reducción de las emisiones de carbono, una transición hacia una economía de bajo carbono y un aumento de la resiliencia general de la comunidad internacional hacia el cambio climático.

1. Introduction

Climate change is one of the most pressing issues of our time. Its impact on the water, energy, food/land, and raw material nexus is immense, and the fragility that imposes is of significant concern. Rising temperatures, changing precipitation patterns, and more frequent and severe weather events can affect the availability and distribution of water, disrupt energy production and distribution, and negatively impact agriculture and food security. These impacts can exacerbate existing vulnerabilities and lead to political and social instability. Developing countries face increased poverty and inequality, a fragility that makes it even more challeng-

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ing to develop adaptation and mitigation measures.

The transition from using fossil fuels to renewable energy sources has increased demands for water (hydropower), land (which requires 50 times more space than coal and 90 - 100 times more space than gas), and critical raw materials [1]. Increased temperatures have resulted in habitat destruction, acidification, and massive runoff of nutrients into the water. Past research [2] has shown that global warming has increased the oligotrophic ocean waters by 6.6 million km^2. Freshwater systems are even more vulnerable to climate change due to their isolation and physical fragmentation within the terrestrial landscape but, more importantly, to unsustainable human exploitation practices.

Changes in climate and precipitation patterns influence natural forests, agriculture, and food security. Droughts, for instance, increase the vulnerability of forests to wildfires and decrease arable land, which can force conversion of forests into agricultural land. This process emits substantial amounts of greenhouse gases and further contributes to global warming. Agriculture, forestry and other land use accounted for 24 % of the total anthropogenic emissions in 2010 [2]. This increases competition for natural resources while decreasing livelihood security.

The net result is a synergetic spiral degradation effect with fewer forests, reduced biodiversity and further deterioration of ecosystems and their services, with the danger of the spiral becoming self-perpetuated until the potential of deterioration is fully exhausted (Figure 1).

Adding to the equation of natural hazards (floods/droughts) as a direct consequence of climate change, the average annual economic losses in Europe are forecasted to be around €23.5 billion by 2050, compared to the €4.6 billion for the period of 2000 - 2012 [2]. The conditions have not been ameliorated. The consequences on environmental and social stability are expected to be vast and long-term.

Past research on how interactions between biophysical effects and climate change impact the water, energy, food/land, raw material nexus, including the social dimension, is limited due to insufficient relevant quantitative models. Additionally, the focus on socio-economic assessments linked to climate change in most countries is restricted to national boundaries without considering transnational issues. Consequently, any available results only address higher-order socio-economic impacts. International policy frameworks developed by the Paris Agreement, the United Nations Sustainable Development Goals (SDGs), and the Sendai Framework for Disaster Risk Reduction, highlight the importance of quantitative indicators and consider the approaches developed by stakeholders, as alternative or complementary measures to assessing vulnerability to climate change. Stakeholder engagement, through more collaborative and consultative approaches, requires meaningful participation of relevant stakeholders throughout the design, development and operational phases of projects. The benefits of public participation, particularly from communities that are directly and indirectly affected by the project, will strengthen both the design (by considering extraneous factors that might not be obvious to the technical teams) and the operational sustainability of the final product, given the community's ownership, ease of use, and added benefits.

This more participative approach ensures that adaptation actions devised today are robust for future biophysical determinants acting upon current social determinants. Carbon Capture Utilisation and Storage (CCUS) integration with hydrogen-related technologies can be part of a defensive solution against the climate change occurred by uncontrolled greenhouse emissions. Proper design of such methods can lead to social acceptance and financial maintenance while increasing resilience. A transition energy period of producing blue hydrogen with the use of CCUS can be replaced ultimately with green hydrogen, where geological hydrogen storage can be facilitated by deploying captured CO_2 as a cushion gas [4-6]. In addition, injection of captured CO_2 in ophiolites can induce serpentinisation to provide "orange hydrogen" [7]. The process significantly impacts the sustainable use of raw materials, energy and water. It removes volatility and brings energy security and socio-economic stability while delivering a mitigation/adaptation solution for climate change. Even in the transportation sector, which is hard to decarbonise, the production of e-fuels from green hydrogen and CO_2 captured from biomass energy, can contribute significantly to the

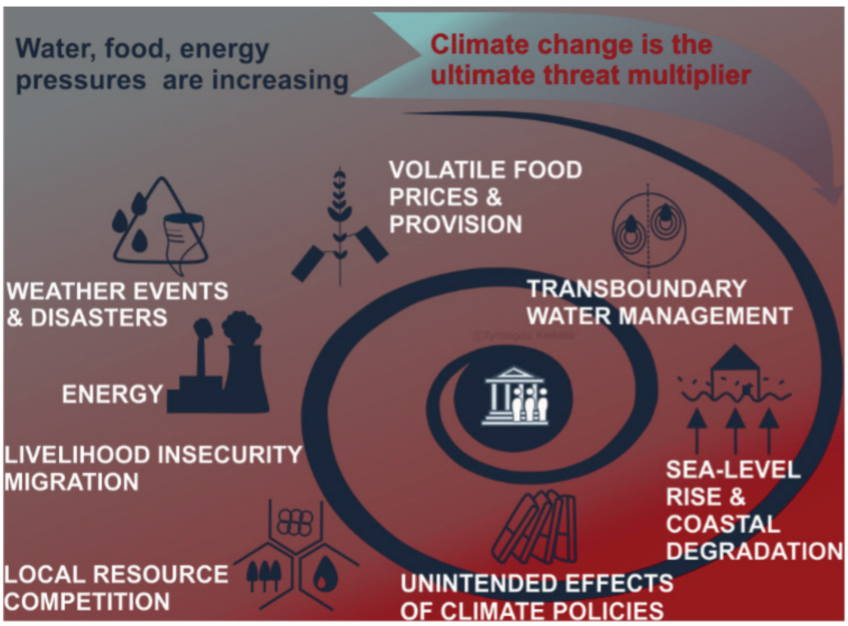

Figure 1: Water-food-energy synergetic degradation spiral, adapted from Wolfmaier et al. 2019 [3].

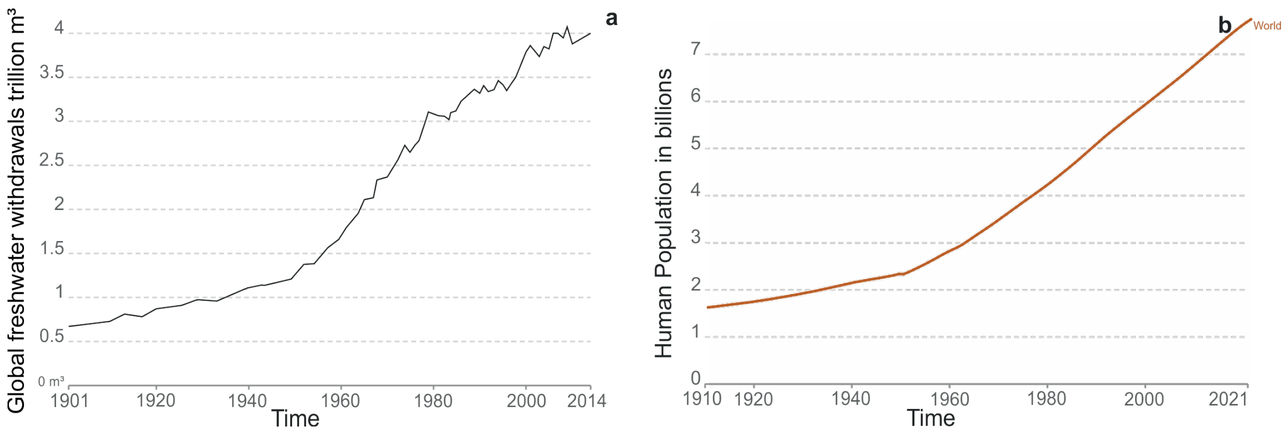

Figure 2: a) Global freshwater withdrawals for agriculture, industry and domestic use since 1900, measured in cubic metres (m^3) per year 13, sourced: https://ourworldindata.org/water-use-stress, Global International Geosphere-Biosphere Programme (IGB), b) Population growth from 1910 to 2021 14, CC BY

sustainability of that particular sector. It is argued that during the early stages of a hydrogen economy, hydrogen will need to be mixed with CO_2 to produce methane or methanol to facilitate the transportation of vast amounts of hydrogen through the existing network of natural gas pipelines [8-10].

2. Challenges and impacts of the energy transition in response to climate change

To mitigate the effects of climate change and remain below the 1.5 °C scenario, the challenge [11] is to adapt society and businesses to ensure economic prosperity and sustainability. Rapid decarbonisation of the global economy is part of the solution [12]. The goal of a net-zero emissions energy system and the economic needs will merge the available technologies and solutions with new options that should gradually replace the older and (un)sustainable ones in the overarching rationale of the energy transition. This transition will be disruptive and must consider the inter-competitiveness and interconnections of the food, water and raw materials industries to ensure the integrity of the ecosystem. In addition, for any 'disruptive' transition to occur with the support of society, the process of introduction needs to be inclusive and transparent (per the SDGs), so that as many people as possible (including governments) understand why the adoption of these technologies is needed, and to encourage ownership of new technologies in the local communities. Technology alone will not provide the solution without widespread systems for encouraging adoption. A brief exploration of the inter-competitiveness is given below.

Climate change, may cause floods in some areas and droughts in others. The latter can cause an increase in the consumption of any available surface water and the over-extraction of groundwater for potable and agricultural reasons. Groundwater extraction is closely coupled with energy consumption, which is required to bring water to the surface. As shallow aquifers become exhausted, deep aquifers will be exploited, further increasing the energy demand particularly in places where water and energy supplies are limited. Thus, creating an endless cycle failing to solve the problem of sustainable resource use. Figure 2 depicts the global freshwater use over the last 113 years [13], with steep increases after 1950. This trend is closely linked with global population growth [14] and, subsequently, food production.

Food production, an absolute necessity to avoid famine, consumes between 70 - 90% of available water resources [15,16]. Figure 3 provides data on food production against water demands. The production of one kg of cheese requires an astonishing volume of 5605 litres of freshwater and one kg of tomatoes needs 370 litres of water [14]. In both cases, the water must be transported or withdrawn from underground reservoirs which, in turn, consumes energy. Furthermore, producing 100g of cheese emits 10 kg CO_2eq, whereas, for one kg of tomatoes, the respective emission is estimated at 2 kg CO_2eq [15,17]. The drive to lower agricultural costs, is leading to the adoption of super-intensive agriculture of high value products, such as avocados or cotton, with much higher level of water consumption and soil exhaustion than traditional agriculture practices.

Importing food to alleviate water shortages transfers the problem elsewhere, as demonstrated by the concept of virtual water [15], i.e. the hidden flow of water in food or other commodities traded from one place to another [16,18]. Food imports can make things worse for countries whose economies are agricultural-based

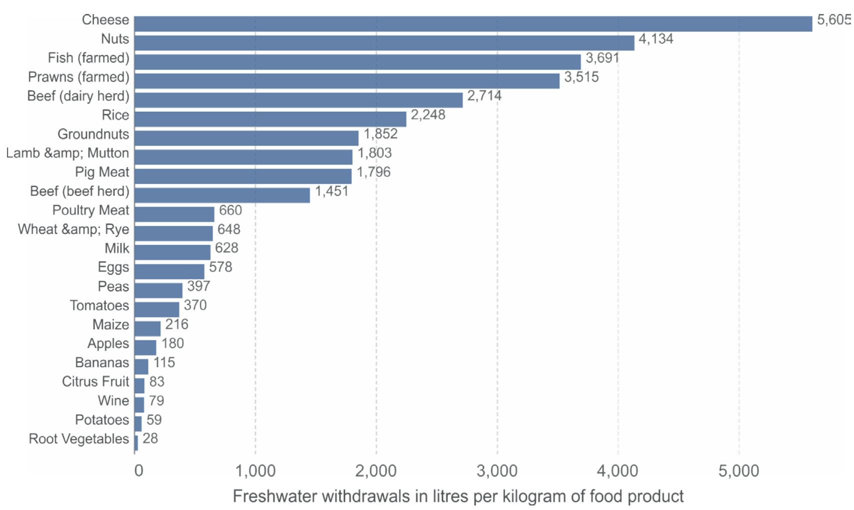

Figure 3: Freshwater withdrawals per kilogram of food product, adopted from Poore, J., & Nemecek, T. (2018) 15 and sourced from https://ourworldindata.org/grapher/water-withdrawals-per-kg-poore, CC BY.

and dependent on food export. Big economies with strong currencies can afford to import large quantities of food from poorer countries, thus depriving the latter of essential food resources and forcing them into energy and water overconsumption. The aforementioned challenge directly makes developing countries poorer and deprives them of resources available for economic development [18]. This over-exploitation can have a detrimental effect on local societies where water is scarce, especially in Asia, Africa, and South America. Under the compound influence of climate change and regional conflicts, affected inhabitants migrate to wealthier nations [19] which are part of the problem and see these immigrants as a social disturbance [20,21].

Society needs to invest heavily in using renewable energy to cover increasing demands for energy and move into a zero-emissions and later, negative emission era. This requires the exploitation of an unprecedented amount of raw materials that the world has ever seen [22] to build the necessary infrastructure and equipment [23-27]. For instance, solar panels for photovoltaic power require up to 40 times more copper than fossil fuel combustion, and wind turbines for harvesting wind power require up to 14 times more iron [28]. More importantly, mining requires fresh water to extract metals and minerals [24]. Thus, large-scale mining will require huge amounts of energy and water, which, as mentioned above, will become scarce due to climate change. The latter will strongly influence and erode the social acceptance of companies involved in mining [29].

In many developed regions, including Europe, mining is not socially acceptable under the "Not in My Back Yard" perception [24,30,31]. Most European needs for critical raw materials for renewable energy infrastructure and batteries are covered by imports from Africa and Asia [32]. Similarly, raw materials follow the same trend as the paradigm presented above on food imports, critical or not. They are imported from developing countries in exchange for hard currency. However, this practice leads to loss of opportunity for development, creating regional competition for available energy, food, water, and raw material resources. Climate change, further enlarges this competition, creating instability, social unrest and violent local conflicts [19,33]. Current research strongly indicates that rising food prices, due to climate change, have acted as catalysts for protests and political unrest [19].

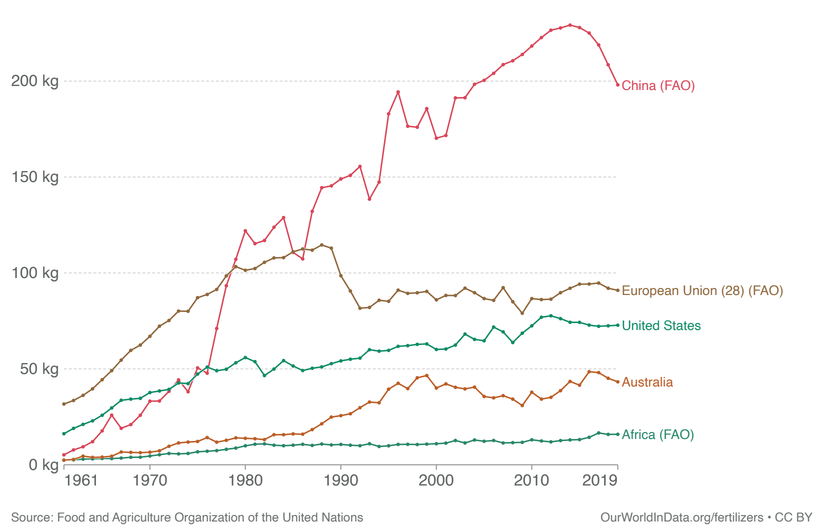

Figure 4: Application of nitrogen fertiliser, measured in kilograms of total nutrient per hectare of cropland, source: Food and Agriculture Organization of the United Nations 39, CC BY.

With temperatures rising, the impacts of climate change will further destabilise already unstable areas [19]. Raw materials mining and renewable energy both require large surface areas, competing with the demand on land for food production or grazing. Additionally, arable land is decreasing, also under the influence of climate change [34]. To make things even more complex, agriculture, forestry, and changes in land use contribute to climate change by emitting 19.9 $GtCO_2eq$, while nitrogen fertiliser production, with the current technology, accounts for a further 0.4 $GtCO_2eq$ of emissions [35]. At the same time, it increases the dangerous dependency of developed regions on vital resources produced elsewhere. This dependency can become an economic weapon used by autocratic regimes, as recently demonstrated during the eruption of a full-fledged war in Ukraine.

Furthermore, new solutions proposed to meet the energy demands must consider potential conflicts with other economic sectors, such as agriculture. For instance, it is proposed that ammonia can be used as an alternative fuel as it is easy to transport and store compared other forms of hydrogen [36]. However, so far, the potential of ammonia as a fuel has not been adequately evaluated against any potential competing needs, such as its use as a fertiliser.

If our society replaces current fossil fuels with ammonia, the amounts required to fulfil our energy needs will be vast. Without a structured approach, such a transition will directly compete with the demands of the fertiliser industry. With an increasing human population [14], the need for food increases; thus, the required quantities of fertilizer will rise, as shown in Figure 4. Furthermore, ammonia is deployed in various industrial activities, such as cotton softening and synthetic fibres [37]. Notably, it is estimated that every kilogram of hydrogen produced from electrolysis requires 9 kg of water [38]. This is typically fresh water, as it is cheaper to clean and deionise. However, it should also be noted that conventional thermal power plants account for 41 % of all freshwater withdrawals in the USA [38].

There is progress from the scientific community in understanding the processes described above and their interconnections, which affect our society. This is partially driven by the SDGs [40-43] and the Paris Agreement, which aims to reduce CO_2 emissions by 60 % [44]. A circular economy, together with capturing emissions technology from existing industrial and power generation processes combined with developing new clean energy sources can facilitate an emissions reduction pathway. Thus, one way to increase resilience to climate change and its effects is to increase the use of natural hydrogen, green hydrogen, and CCUS technologies.

These processes, elaborated further below, can achieve a non-disruptive energy transition while increasing sustainability and resilience, and minimising conflicts [45].

3. Opportunities, proposed solutions and mitigation measures of CCUS and hydrogen

To sustain the quality of life that has been achieved, a new era of energy consumption based on renewable energy is needed. To achieve this, an energy transition is required without compromising development. Current practices of energy conversion can be coupled with carbon capture, which can be (immediately) (re) utilised or stored.

3.1. CCUS - The steps to decarbonisation and net zero emissions

Carbon capture, utilisation, and storage (CCUS) is a technology that involves the capture of carbon dioxide (CO_2) emissions from industrial processes, such as power generation and manufacturing, pipelines for transportation, utilisation sites, and finally injecting the surplus into secure geological reservoirs. The technology helps reduce emissions by preventing CO_2 from entering the atmosphere, thus reducing the impacts of climate change. Deployment of CCUS allows for the current use of fossil fuels for energy conversion with no emissions. It offers the potential for a structured non-disruptive energy transition to renewable energy using current technologies and fossil fuels. The technologies used for CO_2 capture include chemical looping combustion, pre-combustion capture, and post-combustion capture. After being captured, CO_2 can be transformed into various goods and services, including fuels, chemicals, building materials made from waste or minerals, and CO_2 that increases the productivity of biological processes [46]. In addition, geological media can potentially store large quantities of CO_2 in deep saline aquifers, salt caverns, coal seams, abandoned coal mines and depleted hydrocarbon fields. CO_2-mineralisation is an additional option for CO_2-storage that involves the chemical reaction of several rock-types (such as basalts, sandstones and serpentinites) with supercritical CO_2. The same utilization and storage principles can be used for CO_2 from direct air capture (DAC), however, at the moment of writing, this technology is significantly more expensive. The process results in CO_2 sequestration by the formation of carbonate minerals and, under the right conditions, releases hydrogen [7]. This process will be explained further below. The potential uses of CO_2 are vast, with the possibility being converted into e-fuels, chemicals, polymers or applied as aggregates, in new types of cement, or in CO_2-cured concrete through a range of mineralisation techniques. Even direct uses of CO_2 has seen a boost in research, be it in the utilisation for greenhouses, algae growth, or as a heat transfer fluid in enhanced geothermal systems or supercritical power systems [47].

3.2 Reducing the footprint of hydrogen production through CCUS and transitioning to lower emission energy sources

Hydrogen can be burned in turbines or used in fuel cells to generate electricity. It can also be used in fuel cells to power electric vehicles, as a source of domestic and industrial heat, and as a feedstock for industrial processes [48]. Currently, hydrogen is produced using hydrocarbon reforming methods (primarily SMR) with associated CO_2 emissions on the scale of 10-20 tons per ton of H_2 produced (often referred to as "grey" hydrogen). The annual hydrogen production is 120Mt, with only 1% utilising CCUS technologies [48].

CCUS and hydrogen have become increasingly intertwined as a part of the world's efforts to reduce carbon emissions and move towards a low-carbon economy. Low footprint hydrogen production may be achieved by producing hydrogen a) from water electrolysis, b) from natural gas by separating hydrogen from CO_2 through Steam Methane Reforming (SMR) or Auto Thermal Reforming (ATR) and c) from coal gasification. Each method, must always be coupled with CCUS [21,48], which captures the CO_2 instead of emitting it into the atmosphere. The overall reduction of associated emissions could be on a scale of 5-10 times of the current reforming methods.

The Hydrogen Council estimates that demand for hydrogen could exceed 530 Mtpa by 2050. To meet this demand, an increase in productivity is a pre-requisite, and hydrogen produced with the aid of CCUS will be essential, at least in the first years [48], when renewable energy is still penetrating the market on a large scale. Current hydrogen production costs using SMR and CCS are reported to be around \$2/kg [48] benefiting from the advantage of existing infrastructure and assets, making it less expensive than alternative energy sources in the short term. Thus, these production methods may serve as a transitional energy source to achieve climate goals at a reasonable cost without compromising energy diversity and the objective of a low-carbon economy [21], leading to wide-spread usage of renewable energy.

3.3 Hydrogen from renewable energy sources

Hydrogen produced from renewable energy sources such as solar, wind, and hydropower (or "green" hydrogen) offers a further footprint reduction compared to traditional SMR. Electrolysers convert excess electrical energy into chemical energy in the form of hydrogen. When there is a strong demand for energy, fuel cells or engine generators convert chemical energy back into electricity [49]. Currently, the cost of hydrogen production by electrolysis ranges around \$6/kg [48]. Electrolysis is a key component for grid stability and renewable electricity production due to its ability to store energy for long periods of time with minimal losses. Large amounts of hydrogen are produced and subsequently stored either alone or in combination with other gases in underground formations. Hydrogen storage in geological media involves rock/salt caverns and, potentially, porous media such as saline aquifers and depleted oil and gas fields. Captured carbon dioxide can be employed as a cushion gas since it is much denser than hydrogen under typical reservoir conditions; the density segregation in this situation is relatively strong [49].

In a fully decarbonised energy sector, replaced with hydrogen produced with renewable-sourced electrolysis, the annual water use would be approximately 28kg per person per day [38]. Very often, the regions with a high potential for electrolysis, due to the availability of solar conditions, also have water scarcity problems, or they will develop due the effects of climate change. Water for electrolysis will not be transported from a large distance, posing a regional problem resulting from competition for water between electrolysis, agriculture and human consumption. To alleviate this, wastewater or sea water direct electrolysis for hydrogen production can be used. The kind of technology is under development and promising [50].
Furthermore, the use of hydrogen produces the same amount of water as was initially electrolysed. Thus, in large facilities water vapour can be condensed at the point of use and recovered as liquid water [38]. The potential use of treated wastewater for electrolysis may offset local competition for freshwater from other industries. Wastewater facilities offer close proximity to urban areas with easy access, thus facilitating the development of decentralised hydrogen hubs [38]. However, it should be noted that hydrogen production has con-

sequences for climate change and does not provide an ultimate solution. However, it is part of the mitigation measures for climate change and a shift towards sustainable energy [51].

3.4 New and emerging technologies for hydrogen - Synergies with CCUS to retrieve energy and raw materials

In contrast to the previously mentioned technologies, which are energy vectors, hydrogen may also be liberated by inducing serpentinisation or through water coming into contact with geological formations that contain reduced iron, provided that the right conditions of temperature, fluid composition and pressure exist. This is performed by injecting water in situ in identified reactive formations and collecting the hydrogen-saturated water from recovery wells [52]. The process is often referred as "orange" and is similar to the production of natural hydrogen [53-55].

This production method has a great potential for synergy with CCUS since the same formations that naturally produce hydrogen are also the ideal places to store carbon [56]. The natural oxidation of iron and carbon mineralization works extremely well with saltwater or even wastewater. In contrast to electrolysis, which can only be used with high quality water compositions, this significantly reduces the water cost of producing hydrogen without counting the environmental benefits [7].

Geological target formations may also include minerals, such as Li, Ni, and Co, which are of interest to industry. Following the injection, minerals can dissolve, releasing these elements into the percolating fluids. These can then be recovered alongside hydrogen through fractional precipitation. Orange hydrogen does not require as many essential raw materials as electrolysis procedures do. On the contrary, orange hydrogen produces them and therefore differs significantly from its alternatives [7].

Hydrogen production technologies often referred as "gold hydrogen" have rapidly emerged in the recent years. Most commonly, and in this paper, the term "gold" refers to low-footprint hydrogen generated and produced from subsurface reservoirs, although other uses may be found in the literature.

An accumulation of recoverable natural hydrogen has been reported in Mali, with occurrences in other regions of the world being actively discussed [57,58].

On top of that, several technological companies are working on underground conversion of natural gas to hydrogen, using biological (Cemvita - www.cemvita.com) or chemical (Hydrogen Source - www.hydrogen-source.com) conversion of methane. Proton Technologies (https://proton.energy) is focused on gasification/pyrolysis processes to generate hydrogen from heavy oil deposits.

It is also important to remember that associated emissions for any type of hydrogen production will increase with the transportation distance to the end-user. Therefore, localised hydrogen production must be prioritised, with different production types being more advantageous in some regions than others.

3.5 Environmental trade commodities

Intelligent climate and water policies can be achieved by understanding complex interactions between water, food and energy production. The concept of virtual water is an important tool for better understanding how climate change can affect the above-mentioned nexus. Virtual water can also be defined as "the amount of freshwater used for producing goods or services that are exported from one country to another". By understanding how virtual water moves between countries, it is possible to identify where changes in temperature or precipitation may cause disruptions in supply chains. This insight can be used to inform policy decisions that aim to maximize synergies between managed resource sectors while minimizing their vulnerability to climate change impacts.

Given that major climate change is expected to alter the hydrological cycle, policymakers and planners will need to make changes in major practices related to climate change, such as water abstraction regulations, water rights, irrigation systems, land use planning and infrastructure upgrades. To ensure that resource management needs are met under a changing climate, cross-sectoral linkages between policy sectors must be established to maximize synergies while minimizing vulnerability. This paper argues for an integrated framework of policy innovations that considers both sector policies as well as cross-sectoral linkages, which can help decision makers identify how best to address the population's needs under a changing climate. This framework should include strategies for monitoring ecosystem processes, in order to identify early warning signs of resource depletion related to water, food, energy, raw materials and state destabilization.

Cross-sector ecosystem services should be integrated into assessments of policy decisions to ensure that they address climate change, demand for raw materials, food, energy and water resources. The nexus between agricultural food production, energy food and energy water resources is complex, requiring comprehensive consideration of the increasing water diversions and pollution caused by human demand [59]. The need for an integrated approach to managing the water, energy, food/land, raw material nexus is evident; providing water for agriculture while also maintaining wildlife habitats is a delicate balance that requires careful consideration of all systems involved. Policy makers must assess their decisions from a holistic perspective in order to consider the implications of their choices for both humans and the environment. Changes in land use, pollution levels, and resource availability must all be considered when deciding how to best manage these resources.

Climate change mitigation policies should be tailored to the context in which food is produced and how it is traded. Adaptive policy decisions should include new approaches to adaptive food trade that account for future virtual water flows. They must assess population changes, climate land use and estimated land use changes to assess the combined effect of climate change on food security. This would highlight future value of trade decisions and population trends in improving food security and reducing greenhouse gas emissions [60].

There is a strong need to direct the efforts towards developing methodologies to evaluate the environmental assets of natural capital resources related to the water, energy, food/land, raw material nexus. This includes the financial value of adopting nature-based solutions into ecosystem services based on stock and flow models [61-65]. Virtual water provides a conceptual framework for treating water as an internationally traded commodity [16]. Businesses and citizens can employ information and analytical support of natural capital and natural assets for deciding on ecosystem service management in a rapidly changing climate. Financial analysis of both natural capital and asset balance sheets can be aided by databases and maps of the areas of interest. This is achieved by setting an environmental profit-and-loss account to determine: "the cost of ecoservices provided to a company if nature were a business", and "how much would it charge to clean up the 'footprint' left behind by the company?" Integrating these efforts into the nexus with security/ disaster risk management, used by the finance sector, will provide the natural resources and ecological services with their insurance value.

To address the competition of resources, water markets are an efficient approach, as they allow for the allocation of limited water resources in an optimal way. The water demand of each consumption region should be calculated to determine the economic impact on the basin and its corresponding surpluses. Furthermore, land use change can significantly affect the availability and quality of water supply, so it should be considered when calculating economic impacts [66,67].

4. Conclusions and future trends

It is recognised that CCUS is the least costly and (in some cases) least disruptive option, but the full social and economic value of the investment require effective communication. It is essential to realise that CCUS provides multiple services: (1) To the emitter, especially for hard-to-abate industries like steel, cement and waste incineration - CCUS takes care of emissions; (2) To the public - CCUS contributes to mitigating climate change by facilitating the decarbonisation of multiple sectors and distributed emissions sources over the long term, through a balanced and equitable transition. CCUS does not only 'deal with waste from industry' but also deals with the side effects of the products that consumers are using. Utilisation allows stepping away from waste management to resource management, enabling more efficient use of resources and a more positive perception of the technology. This is a wider social and sustainability dimension that directly involves consumers. Therefore, placing the responsibility of consumers at the core of what CCUS provides, and communicating a business case and a narrative that explains what CCUS will deliver to the public, consistent with their expectations, is critical [45].

Increasing the use of locally produced natural hydrogen, electrolysis with renewable energy sources and CCUS technologies can help increase the resilience of countries to climate change and its effects. Hydrogen can be used to reduce emissions and store energy, while CCUS can be used to capture and store CO_2 emissions from industrial processes. By increasing access to clean water, energy, food/land and raw materials, the application these technologies can reduce poverty and inequality and increase the ability of countries to adapt to climate change.

Virtual water is an important resource management concept for the water, energy, food/land, raw material nexus in the context of climate change. It provides a framework to understand the sector-specific opportunities and threats in terms of adaptation, mitigation and sustainable development. When evaluating the impacts of CCUS on natural resource sectors, one must consider its role in sustainable climate change mitigation, including food-related ecosystem processes. Reviews of CCUS pathways have revealed potential opportunities for energy agriculture, energy water, and energy food. These pathways can be used to reduce emissions from energy sectors while helping to meet targets for mitigating climate change. Hydrogen has emerged as a crucial component of strategies for adapting to climate change. It provides an affordable alternative to traditional fuels like coal or oil and has the potential to reduce emissions from energy production and other sectors. Additionally, hydrogen provides a mechanism for storing renewable energy during periods of peak demand.

Ammonia production using renewable energy sources can provide an alternative fuel or fertilizer that does not rely on fossil fuels. Moreover, substitution of feedstocks for chemical production can help reduce emissions from methane and other greenhouse gases.

Inclusion of stakeholders in the process of major transitions to new technologies is not only limited to CCUS. Societal attitudes to concepts such as virtual water, the use of hydrogen as a replacement fuel, and the connection between groundwater management and sustainability, need to change. Policies that introduce new approaches require ownership by the communities, and investment in education, communication and visible demonstration sites are critical for getting people involved. Governments need to adopt the concepts with a more holistic approach, encouraging societal ownership and adoption.

The use of the described technologies and concepts can contribute to the mitigation of global climate change, by reducing carbon emissions and helping to reduce circular economy strategies. It can also facilitate carbon trading and create new economic opportunities for countries to transition their energy structures, to mitigate climate change. Applying circular economy strategies to raw materials and hydrogen can improve energy efficiency, transform energy structures and contribute to mitigating objectives related to climate change. The strategies also enable the transition from fossil fuels to electrification through the application of digital technologies. Electrification and fuel switching are also crucial components of the plans to transition away from a high-carbon intensity economy.

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News corner:
Compiled by Anita Stein, EFG Secretariat

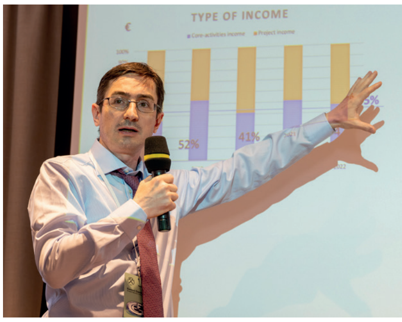
New EFG President: David Govoni

The EFG Board and Secretariat are pleased to welcome David Govoni as the new EFG President.

Following the election held in November 2023, the start of David Govonis' term became official after the 82nd Council Meeting held in Belgrade on 20 and 21 May 2023.

David is a highly experienced geologist with over 20 years of international experience in the mining and quarrying sector. He possesses a diverse background in various technical areas, ranging from exploration and operation, to expertise in business development, permitting, and sustainability challenges, with a particular focus on the industrial minerals sector. David is a member of CNG and EurGeol since 2012, and he has held the position of Fellow of the Institute of Quarrying since 2011. Currently, he holds the position of Geology and Mining Manager at Unicalce Group, one of Italy's leading companies in the industrial minerals sector. Furthermore, David has served as an expert in project evaluation for the European Commission and the European Institute of Technology – Raw Materials. He has held multiple leadership roles in numerous associations and technical committees, actively contributing to the organisation of national and international congresses, as well as training activities in various countries.

We invite you to learn more about David and his vision for EFG in this interview, which we had the opportunity to record at the CNG GeologiTV studio in Rome: ***https://youtu.be/rqI3PmJUsng***



EFG President David Govoni at the 82nd Council meeting in Belgrade.

Last but not least, we express our gratitude to Past President Marko Komac for his dedicated work and commitment throughout the years!

A stronger voice for geoscience: EuroGeoSurveys and European Federation of Geologists launch strategic partnership for increased impact

EuroGeoSurveys' Secretary General Julie Hollis and EFG Executive Director Glen Burridge signing the Memorandum of Understanding in Brussels.

EuroGeoSurveys (EGS) and the European Federation of Geologists (EFG) recently teamed up to create a bigger impact for geoscience. By signing a memorandum of understanding, both organisations lay the foundation for a strategic partnership with a singular goal of bringing the solutions of geoscience to the forefront and paving the way for a sustainable future.

To officially launch this strategic alliance, EFG and EGS are already collaborating on a joint Public Relations Strategy for European Geoscience. The agreement also involves close cooperation between expert panels, scoping of relevant project opportunities, and coordination in the field of member services.

EFG President Marko Komac welcomed the agreement, stating:

"One Earth. One science that helps to understand it – geology. By signing the MoU between EFG and EGS, the two umbrella organisations will join forces, knowledge, experience and resources for a sustainable future."

According to EGS President Christophe Poinssot, *"this MoU represents a major milestone in EuroGeoSurveys' efforts to collaborate with like-minded organisations and promote the role of geoscience in driving sustainable development in Europe. Through our close cooperation, we will be able to leverage the expertise of our respective expert panels and support our shared mission. I am confident that this collaboration will be a fruitful one and bring benefits to all involved".*

Together representing more than 50,000 European geologists, both from the public and the private sectors, EGS and EFG are committed to working hand in hand to achieve a joint vision.

Submission of articles to European Geologist Journal

Notes for contributors

The Editorial Board of the European Geologist journal welcomes article proposals in line with the specific topic agreed on by the EFG Council. The call for articles is published twice a year in December and June along with the publication of the previous issue.
The European Geologist journal publishes feature articles covering all branches of geosciences. EGJ furthermore publishes book reviews, interviews carried out with geoscientists for the section 'Professional profiles' and news relevant to the geological profession. The articles are peer reviewed and also reviewed by a native English speaker.
All articles for publication in the journal should be submitted electronically to the EFG Office at ***info.efg@eurogeologists*** according to the following deadlines:

- Deadlines for submitting article proposals (title and content in a few sentences) to the EFG Office (***info.efg@eurogeologists.eu***) are respectively 15 July and 15 January. The proposals are then evaluated by the Editorial Board and notification is given shortly to successful contributors.
- Deadlines for receipt of full articles are 15 March and 15 September.

Formal requirements

Layout

- Title followed by the author(s) name(s), place of work and email address,
- Abstract in English, French and Spanish,
- Main text without figures,
- Acknowledgements (optional),
- References.

Abstract

- Translation of the abstracts to French and Spanish can be provided by EFG.
- The abstract should summarise the essential information provided by the article in not more than 120 words.
- It should be intelligible without reference to the article and should include information on scope and objectives of the work described, methodology, results obtained and conclusions.

Main text

- The main text should be no longer than 2500 words, provided in doc or docx format.
- Figures should be referred in the text in italic.
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